



TAMPEREEN TEKNILLINEN YLIOPISTO  
TAMPERE UNIVERSITY OF TECHNOLOGY

HANNE KOSKINIEMI  
DATA CENTER COOLING

Master's thesis

Examiner: Reijo Karvinen  
The examiner and topic of the thesis  
were approved by the council of the  
Faculty of Natural Sciences 13 January 2016

## ABSTRACT

**HANNE KOSKINIEMI:** Data center cooling

Tampere University of Technology

Master of Science Thesis, 55 pages, 4 Appendix pages

May 2016

Master's Degree Programme in Environmental and Energy Technology

Major: Fluid dynamics

Examiner: Professor Reijo Karvinen

Keywords: data center cooling, PUE, free cooling, district cooling

The goal of this thesis was to examine possibilities to improve energy efficiency of data center cooling. Data centers form a ground for the telecommunication business. Energy consumption of the data centers is already globally significant because data centers consumed 1.1-1.5 % of world's electricity use in 2010, and about 40 % of that is used for cooling. Enhancement of the data center cooling has a good potential to reduce energy consumption, greenhouse gases, and costs of telecommunication.

This thesis is divided into two parts. The first part will offer a basic theoretical background for the data centers and their cooling systems as well as issues related to thermal management of data center. The second part consists of case study made for Finnish data centers locating part of the office building. Power usage effectiveness (PUE) were inspected and evaluated for the data centers of the building. The close liquid cooled system were compared to the traditionally air cooled system using measurements. Air flow problems at the data centers were discussed. The effects of free cooling and district cooling to the cooling system and energy consumption were discussed.

PUE-value of the examined building varied between 1.2 and 1.8. Comprehensive, real-time and partial monitoring of PUE is demanding, but inserting a few fixed measurements, PUE-value can be defined. Using close liquid cooling, the power density of IT equipment can be higher than with traditional air cooling. Close liquid cooling had minor effect on the PUE-value. The traditional vapor compression cooling system is energy intensive, but it can be replaced, entirely or partly, by free cooling which utilizes coldness of outdoor air, water or ground. District cooling would decrease PUE-value and energy consumption of cooling, especially in summer, when air cooling based free cooling is not in use.

## TIIVISTELMÄ

**HANNE KOSKINIEMI:** Tietokonesalin jäähdytys

Tampereen teknillinen yliopisto

Diplomityö, 55 sivua, 4 liitesivua

Toukokuu 2016

Ympäristö- ja energiatekniikan diplomi-insinöörin tutkinto-ohjelma

Pääaine: Virtaustekniikka

Tarkastaja: professori Reijo Karvinen

**Avainsanat:** tietokonesali, jäähdytys, PUE, vapaajäähdytys, kaukojäähdytys,

Tässä diplomityössä tutkitaan mahdollisuuksia tietokonesalin jäähdytyksen energiatehokkuuden parantamiseen. Tietokonesalit ovat tietoliikennealan perusta. Tietokonesalien energiankulutus on maailmanlaajuisesti merkittävä, sillä maailman sähkönkulutuksesta vuonna 2010 kului 1.1-1.5 % tietokonesaleihin, ja tästä noin 40 % käytetään jäähdytykseen. Tietokonesalien jäähdytystä tehostamalla voidaan vähentää tietoliikennealan energian kulutusta, kasvihuonepäästöjä ja kuluja.

Diplomityö on jaettu kahteen osaan. Ensimmäisessä osassa käsitellään perustietoja tietokonesaleista ja niiden jäähdytysjärjestelmistä sekä lämmönhallintaan liittyvistä asioista. Toinen osa koostuu tapaustutkimuksesta, joka tehtiin toimistorakennuksen yhteydessä sijaitseviin tietokonesaleihin. Rakennuksen tietokonesalien PUE (Power usage effectiveness) –arvon laskentakaava tarkastettiin ja määritettiin uudelleen. Suoraan laitetelineisiin tuotua nestejäähdytystä verrattiin perinteiseen ilmajäähdytykseen mittausten avulla. Tietokonesalien ilmanvirtauksen ongelmia käsiteltiin. Lisäksi tutkittiin vapaajäähdytyksen ja kaukojäähdytyksen vaikutuksia energiankulutukseen ja jäähdytysjärjestelmään.

Tietokonesalien PUE-arvo tutkitussa rakennuksessa vaihteli 1,2 ja 1,8 välillä. Kattava, reaaliaikainen ja osittainen PUE:n seuranta on vaativaa, mutta muutamia pysyviä mittauksia lisäämällä PUE-arvoa voidaan tarkentaa. Työn yhteydessä toteutetun mittauksen perusteella suoraan laitetelineisiin tuotu nestejäähdytys mahdollistaa suuremman tehokkuuden tietokonesalissa kuin perinteinen ilmajäähdytys, mutta PUE-arvoa se ei juuri laskenut. Perinteinen kompressorijäähdytysjärjestelmä on energiantensiivinen, mutta suotuisassa ilmastossa se voidaan korvata kokonaan tai osittain vapaajäähdytyksellä, joka käyttää jäähdyttämiseen ulkoilman, veden tai maaperän kylmyyttä. Kaukojäähdytys hyödyntää meri- tai järvivettä ja se laskisi PUE-arvoa ja energiankulutusta erityisesti kesällä, jolloin ilmajäähdytykseen perustuva vapaajäähdytys ei ole käytössä.

## PREFACE

This Master of Science thesis was divided into two parts. Case study part was made for the company who gave the subject for the thesis. I would like to thank them for a guidance and financial support. Next, I would like to thank my examiner Professor Reijo Karvinen for his guidance during the process.

And last, I would like to say thank for my family. Warm tanks for Antti for his endless encouragement and support, and for my wonderful kids who teach me everyday something new.

Tampere, 25<sup>th</sup> of May 2016

Hanne Koskiniemi

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APPENDIX A: Results of measurements and calculations to determine partial-PUE in DC1 and DC2

## LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating current
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CFD	Computational fluid dynamics
COP	Coefficient of performance
CRAC	Computer room air conditioner
CRAH	Computer room air handler
DC	Direct current
EC	Electrically controlled
ERE	Energy reuse effectiveness
ESD	Electrostatic discharge
ICT	Information and communication technology
IT	Information technology
MCS	Modular cooling system
PDU	Power distribution unit
pPUE	Partial power usage effectiveness
PUE	Power usage effectiveness
UPS	Uninterruptible power supply
WC	Water cooled
$c_p$	Specific heat capacity
$\varepsilon_p$	Coefficient of performance
$\rho$	Density
$\eta$	Efficiency
$g$	Acceleration of gravity
$h$	Height
$n$	Speed of rotation
$p$	Pressure
$P$	Power
$Q$	Heat
$\dot{Q}$	Thermal transfer rate
$\dot{V}$	Flow rate

# 1. INTRODUCTION

A data center industry has grown radically during past two decades as telecommunication industry has grown. Globally, data centers consumed 1.1 -1.5 % of world's electricity use in 2010 (Koomey 2011). As almost all the electrical power supplied to the server is dissipated into heat, cooling demand is significant (Ebrahimi 2014). Nearly 40 % of the energy consumed in data center is used for the cooling, thus the cooling has a significant role in a data center operation as economic and ecologic point of view (Dai et al. 2014, p.8). An improvement of cooling methods may have major impacts on the energy efficiency and greenhouse gases of telecommunication industry.

This thesis is divided into two parts. The first part, Chapters 2-7, will offer a basic theoretical background for the data centers and their cooling systems as well as issues related to the thermal management of data center. The second part, Chapter 8, consists of the case study made for a Finnish data center.

There are several tools for the improvement of the data center energy efficiency. With thermal and airflow management, environmental conditions of the data center are kept in the required levels to ensure reliable, safe and efficient operation of the data center. Energy efficiency metrics of the data center, such as power usage effectiveness (PUE), and data center monitoring are guidelines for the IT managers to operate data centers with high-energy efficient and economical manner. Metrics are used for self-improvements, comparison to other data centers, improve operation of the data center, site selection or design and assist in the selection of a hosting data center (Patterson 2012, p.241).

A predominant cooling method of data centers is air cooling because of its wide usage in a computer cooling, proven high reliability, and lower initial and maintenance costs compared to other cooling methods (Ohadi et al. 2012). But as the energy intensity of IT equipment has increased and the energy efficiency requirements have tighten, traditional air cooling methods have exceeded their capability limit. Close liquid cooling, direct liquid cooling and two-phase cooling are alternatives for the traditional air cooling to manage grown cooling demand.

A cooling liquid is traditionally produced by a vapor compression cooling system. This energy intensive cooling source can be replaced entirely or partly by the free cooling. The free cooling utilizes coldness of outdoor air or water for the data center cooling, and it is one of the most prominent ways to improve energy efficiency of a data center (Malkamäki & Ovaska 2012). A cooling strategy and growing heat loads of the data center also influence on the safety and reliability of the data center.



In the case study, the issues discussed above were examined in the data centers locating part of the office building. Power usage effectiveness (PUE) were evaluated for the data centers of the building. A close liquid cooling system was compared to the traditionally air cooled system using measurements. Air flow problems at data centers were also discussed. The effects of free cooling and district cooling implementation to the cooling system and energy consumption were discussed.

## 2. DATA CENTER

Telecommunications industry has a significant role in almost every sector of society, globally, and data centers form the ground of the information technology. As telecom industry has grown, also energy consumption to run telecom infrastructure has increased. Major part of operation costs of telecom industry comes from energy consumption. Energy intensity of data center is 10 times or more larger than normal office building. (Dai et al. 2014) Globally, data centers consumed 1.1 -1.5 % of world's electricity use in 2010 (Kooimey 2011). In industrial countries, number is about 1.5 – 3 %. Half of that energy was used for power and cooling infrastructure supporting electronic equipment. In Smart 2020 -report (2008) it was calculated that 2 % of global CO<sub>2</sub> emissions (830 megatons) came from telecom industry in 2007 and amount would increase annually 6 % until 2020. One quarter comes from materials and manufacturing and rest is generated during operation of the devices. In EU, there is a target to reduce overall greenhouse gas emission by 20% until 2020 compared to 1990 level (EU greenhouse gas emissions and targets 12.11.2014). As cooling has a significant role in data center operation as economic and ecologic point of view, enhancement of cooling methods may have major impacts when improving energy efficiency of telecom industry and reduce greenhouse gases.

A data center is a space to house ICT (information and communication technology) equipment as servers, switches, and storage facilities, and to control the environmental conditions (temperature, humidity, and dust) to ensure reliable, consistent, safe, and efficient operation of the ICT systems (Rambo & Joshi 2007). A data center is generally organized in rows of racks (Kant 2009). A rack is a standardized metal frame or enclosure for mounting IT (information technology) equipment modules, and rack's dimensions are 1.98 m in height, 0.58 - 0.64 m in width and 0.66 - 0.76 m in depth (Ebrahimi et al. 2014). Servers can be also housed in a self-contained chassis, which contains own power supply, fans, backplane interconnect, and management infrastructure (Kant 2009). A single chassis can house 8 to 16 blade servers (Kant 2009).

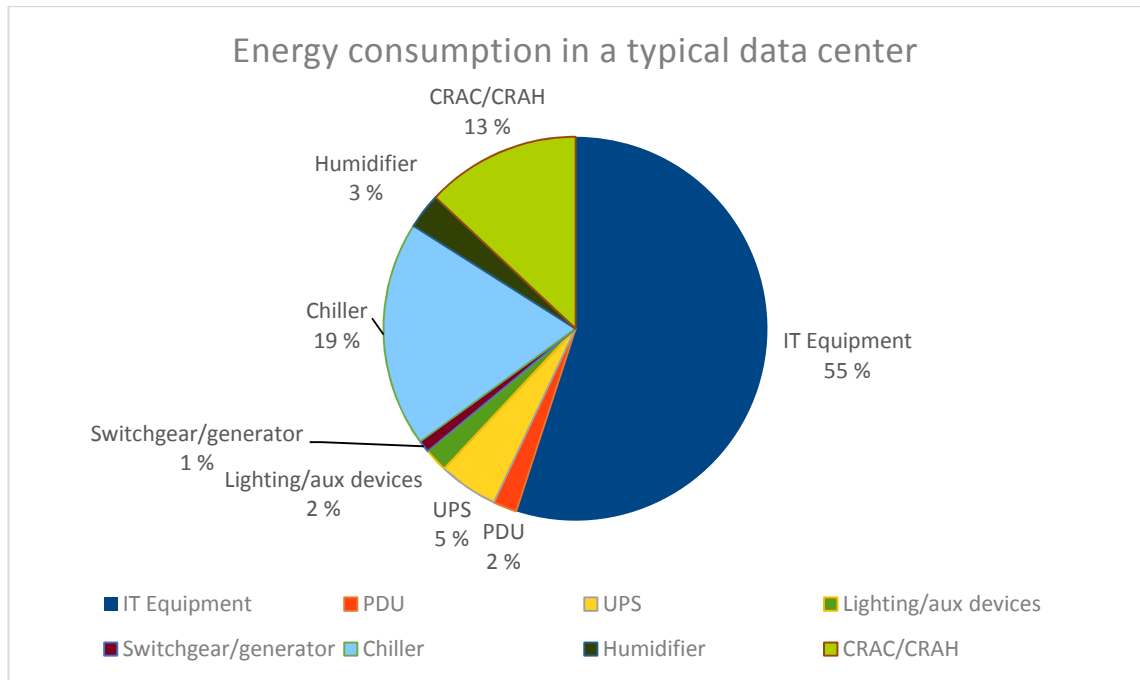
### 2.1 Energy flow of data center

Equipment in data center can be divided in four categories: IT equipment, power equipment, cooling equipment, and miscellaneous component loads, which include lighting and fire protection system. IT equipment includes servers, storage devices and telecom equipment, and supplemental equipment as workstations used to control the center. Main objects of data center are to store data and provide access to the data when requested. (Dai et al. 2014, p.9)

Power equipment include power distribution units (PDU), uninterruptible power supply systems (UPS), switchgear, generators and batteries. Power supply need to be reliable and PDUs and UPS systems are normally redundantly deployed. If utility power fails, generator starts and becomes the active power for data center. UPS systems are used to ensure uninterrupted power supply. UPS systems convert input AC (alternating current) power to DC (direct current) to charge batteries, which provide temporary power in case of power supply interruption. And again UPS will convert DC back to AC for the equipment in data center. UPSs are all the time idle mode and consume significant amount of energy. (Barroso 2013) Efficiency of new UPS systems are about 90-97 % on idle mode (Motiva 2013). To avoid extra heat load in data center, UPSs are usually housed in separate room. PDU units receive power from UPS systems and convert and distribute higher voltage power into many 110V or 220V circuits. A typical PDU can supply 75-250 kW of power. (Barroso et al. 2013)

Cooling equipment consists of chillers, computer room air-conditioning (CRAC) and air handling (CRAH) units, cooling towers and automation devices. Cooling air for ITE is provided by CRAC or CRAH units straight or through raised floor. To avoid mixing of hot and cold air, racks are positioned to form hot and cold aisles. Hot air rises up and recirculates into CRAH. In modern data center, hot and cold aisles can be separated from each other with curtains or hard partitions. Fans are used to circulate air through cooling units and through IT equipment. Air is cooled down inside the CRAH unit by cooling water or liquid coolant, which is pumped to chiller or cooling tower for cooling. (Dai et al. 2014, p.12)

Based on survey of 500 data centers approximate energy distribution in typical data center with PUE=1.8 is presented in *Figure 1* (Dai et al. 2014, p.10). Definition of PUE (power usage effectiveness) is presented in chapter 4.2. Generally, when PUE is larger proportion of cooling is larger. As almost 40 % of energy consumption in data center is used for cooling, enhancing cooling performance is a good way to reduce overall energy consumption of the telecom industry.



**Figure 1. Power distribution in typical data center with PUE=1.8. Values are based on survey of 500 data centers. Adapted from (Dai et al. 2014, p.10) (Uptime Institute 2011).**

Besides enhancing cooling, there is also other ways to improve energy efficiency of data center. Development of efficient electronics is one of the most important aspect. As utilization rate of servers may be 10-15 % of their full capacity, an effective way to save energy is to increase the utilization of servers. Also software development, efficient management and virtualization are methods to reduce number of working servers and still achieve same performance, hence amount of auxiliary equipment may be reduced. (Dai et al. 2014) In this work, it is focused on energy efficiency of cooling and these other ways to enhance energy efficiency, are not discussed more carefully.

## 2.2 Data center thermal loads

As data center floor area is often directly proportional to costs and as demand of ITC has increased, more compact and higher power modules have been designed and produced (Ebrahimi et al. 2014). More densely packed servers may lead situation that racks generate in excess of 60 kW of heat while traditional air cooling is capable to remove cooling capacities in order of 10 – 15 kW per rack (Marcinichen et al. 2012).

A server is the smallest data processing unit in data center and microprocessor chips are the major power dissipation components in servers (about 50 % of total server power) (Ebrahimi et al. 2014). Performance of microprocessors is increased and their heat fluxes are in order of  $100 \text{ W/cm}^2$  which exceeds maximum heat removal capacity of air, which is about  $37 \text{ W/cm}^2$  (Marcinichen et al. 2012). Ebrahimi et al. (2014) have summarized total heat load of standard and blade servers, which are typically 300-400 W for standard

servers, but can reach up to 525 W at highly populated servers, and around 250 W for blade servers.

As electronics dissipate a large amount of heat, overheating may cause malfunction, melt or burn. Before these consequences, normally safety devices on the server racks detect high temperature and shut down the equipment causing interruption of data center operation. (Patankar 2010)

When compared data center energy dissipation with capacity of conventional HVAC systems, importance of design and manufacture of thermal management systems can be seen. Accurate information of the maximum thermal loads and temperature limits in each data center component is a necessity of successful design and thermal management of data center. (Ebrahimi et al. 2014)

### 3. AIR FLOW AND THERMAL MANAGEMENT

One object of the air flow and thermal management is to keep environmental conditions such that they ensure reliable, safe and efficient operation of ICT (information and communication technology) (Kant 2009). Challenges of data center thermal managements are among others dynamic nature of IT equipment heat load, heterogeneous air distribution environment and absence of well-defines paths of air. Each data center is unique and application of guidelines is left to the end user. Thus most data centers are managed based on intuition or accumulated experience. (Kumar & Joshi 2012, p. 43)

#### 3.1 Environmental conditions of data center

Environmental conditions of data center must be such that they ensure reliable, safe and efficient operation of ICT systems (Kant 2009). Conditions to take into account are for example temperature and its stability, humidity and dust. High temperature and especially variability in temperature reduce long term reliability of ITE (El-Sayed et al. 2012). In addition, hot spots may lead to thermal shut down of ITE (Patankar 2010). High humidity can cause condensate, which may cause corrosion and electrical shorts inside the data processing equipment. Condensate may also form on the heat exchanger cooling coils in the CRAH units and reduce heat transfer from air to cooling water circle. Low humidity may lead to electrostatic discharge (ESD). ESD is a safety hazard for the people working in the data center, and could shut down and damage the IT equipment. Depending on the moisture content of the air, the CRAC unit may need to humidify or dehumidify the air. (Kumar & Joshi 2012, p.94) Airborne dust have mechanical effects as obstruction of cooling airflow, abrasion, and optical interference, chemical effects as corrosion and electrical shorts, and electrical effects as impedance changes and electronic circuit conductor bridging (2011 Gaseous and particulate contamination guidelines for data center 2011). All of these result in a significant increase in operating cost (Kumar & Joshi 2012, p. 42).

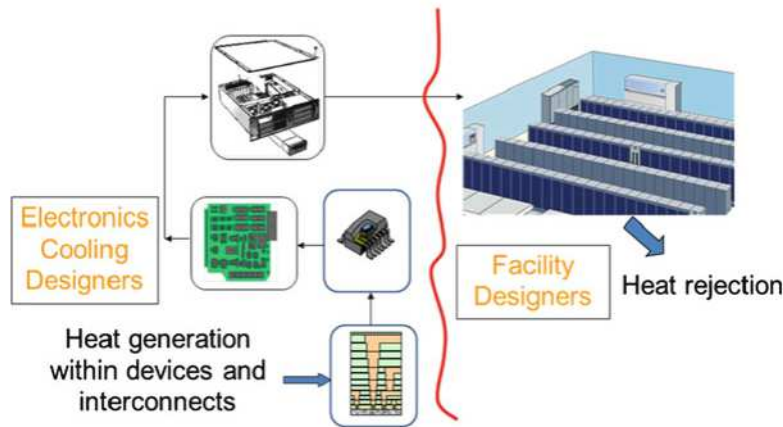
2011 ASHRAE Thermal Guidelines gives recommended and allowable environmental specifications for the datacenters. Recommended values give limits under which ITE would operate most reliably and achieve still reasonably energy efficient operation. Allowable values give limits which are allowed for a short periods without affecting overall performance and reliability of the ITE. Datacenters are divided up into six classes. Class A1 is datacenter including tightly controlled enterprise servers and storage products. Classes A2-A4 are datacenters including volume servers, storage products, personal computers and workstations with some control. Class B is an office and class C is a factory environment. The bigger the class number the broader allowable temperature range is. ASHRAE Thermal Guidelines are collected into the Table 1.

**Table 1. 2011 ASHRAE Thermal Guidelines for data centers.**

Classes	Equipment Environmental Specifications							
	Product Operations					Product Power Off		
	Dry-Bulb Temperature (°C)	Humidity Range, non-Condensing	Maximum Dew Point (°C)	Maximum Elevation (m)	Maximum Rate of Change (°C/h)	Dry-Bulb Temperature (°C)	Relative Humidity (%)	Maximum Dew Point (°C)
<b>Recommended</b>								
<b>A1 to A4</b>	18 to 27	5.5 °C DP to 60% RH and 15 °C DP						
<b>Allowable</b>								
<b>A1</b>	15 to 32	20% to 80% RH	17	3050	5/20	5 to 45	8 to 80	27
<b>A2</b>	10 to 35	20% to 80% RH	21	3050	5/20	5 to 45	8 to 80	27
<b>A3</b>	5 to 40	-12 °C DP & 8% RH to 85% RH	24	3050	5/20	5 to 45	8 to 85	27
<b>A4</b>	5 to 45	-12 °C DP & 8% RH to 90% RH	24	3050	5/20	5 to 45	8 to 90	27
<b>B</b>	5 to 35	8% RH to 80% RH	28	3050	NA	5 to 45	8 to 80	29
<b>C</b>	5 to 40	8% RH to 80% RH	28	3050	NA	5 to 45	8 to 80	29

### 3.2 Thermal management

The thermal management system must be capable of handling the increased thermal loads and maintain the temperature of electronic components at a safe operational level (Ebrahimi et al. 2014). Thermal management of data center consists of multiple length scales, from tens of nanometers at chip level to hundreds of meters at facility. As can be seen in Figure 2, traditionally thermal management problems have been divided into two separate fields; electronics' cooling designers have been dealing with heat transfer on electronic devices and facility designers have been dealing with ventilation and air-conditioning (Joshi & Kumar 2012). While power density and requirements for energy savings in data center have increased, thermal management covering all length scales have become essential. Current design methods depend much upon empirical models of thermal coupling between various components instead of analytic design methods (Kant 2009).



**Figure 2. Historically thermal management of data center has been divided between electronics cooling designers and facility designers (Joshi & Kumar 2012, p.3).**

At chip level scale, different methods to enhance heat dissipation from chip are managed including design of effective heat sinks and micro heat exchangers attached to the chip. At server level scale solutions are integrated with the chip carrier or printed circuit board and include liquid cooling using cold plates. Next scale is at chassis level, in which heat from servers is transferred to cooling air. At cabinet or rack level scale, air cooling is the most popular solution but at higher heat loads it needs to be replaced or extended with other techniques, which are discussed later. At room level scale, cooling is normally achieved through CRAH units and cooling air is delivered to the racks, for example, through perforated tiles which are placed over a raised-floor plenum. At plenum level scale, air-delivery plenums including flow through perforated tiles are managed. (Joshi & Kumar 2012)

Numerical modeling and simulation are usually used as a part of thermal management and designing cooling system. Both CFD (computational fluid dynamic) calculations, including meshing and setting boundary conditions, and obtaining and interpreting experimental results require expert knowledge. Time and resource constraints prevent the use of most accurate models, as direct numerical simulation or large eddy simulation, proper meshing, and grid sensitivity analysis. A compromise is to compare simulation results of a detailed model and a simplified model with an acceptable accuracy level of about 85 %. (Garimella et al. 2012)

### 3.3 Airflow management

Airflow management can be counted as a part of data center thermal management and it is maybe the most important aspect of it (Kumar & Joshi 2012, p. 39). The general object of air flow management is to minimize air bypassing, which is the primary source of thermodynamic inefficiency in an air-cooled data center (Kumar & Joshi 2012, p. 43). Air bypassing leads to intermingling of cool and hot air, increases equipment intake temperatures and form hot spots. Problems caused by air bypassing are often resolved by



reducing air supply temperature or raising air flow volumes. Both of these methods would lead to the increased energy costs. (Newcombe et al.). It is estimated that the amount of cooling air used in the most data centers is 2.5 times the required amount (Patankar 2010). In an air-cooled data center, as discussed in chapter 5.1, hot and cold airstreams can be isolated physically arranging the racks in alternate rows to form hot and cold aisles. Next task to prevent air mixing is to supply cold air and extract hot air in the most effective way. (Kumar & Joshi 2012, p. 43)

Energy needed to deliver air to and from the IT equipment consist of the flow resistance within the data center. System resistance is a function of the layout of the room, type of air delivery system, pressure drop across the distribution system, and flow rate. It is the sum of static pressure losses across all the components in air delivery in the data center, and provides information on the static pressure head to size fans in the CRAC. System resistance curve can be generated using component pressure drop data from manufacturer or generated by using empirical measurements or from a CFD model. Any changes in the data center equipment or layout made, effects the pressure drop and operating point. (Kumar & Joshi 2012, p. 47)

Pressure variation across the CRAC unit is largest in the static pressure curve, and is a function of the CRAC fan speed. As the pressure drop across the CRAC is not much affected by static pressure variations across plenum, perforated tiles and room, they can be analyzed independently. Room pressure variations are insignificant compared to pressure variations across the perforated tiles and the subfloor. Plenum pressure distribution is affected by the plenum height, tile open area, blockages in the under-floor plenum, and air leakage through the raised floor. Rack-level air distribution is affected by server fan speed, pressure drop across the server, and a number of external factors, such as perforations on the rack doors, obstruction of cables, rear door heat exchanges and chimneys. Furthermore, external pressure drop is affected by the momentum of air delivered to the rack. Effect of buoyancy, caused by temperature gradients, become significant at higher rack densities. (Kumar & Joshi 2012, p. 53-89)

The airflow managing must balance both thermal environment and energy savings. But while airflow can be individually tuned to meet demands of IT equipment, it is not possible for temperature and humidity. (Kumar & Joshi 2012, p. 81) One way to have energy savings is to increase set points, but before set points can be raised, air flow management actions need to be tackled. With air flow management actions, energy savings can be achieved without risk for equipment overheating and assuring more uniform equipment inlet temperatures. (Newcombe et al.)

One challenge at the data center air flow and thermal management is a short lifecycle of servers (3-5 years) compared to building facilities (15-25 years) (Patterson 2012, p. 238)

and the dynamic nature of IT business (Patankar 2010). That may cause mismatches between the IT technology and the supporting infrastructure, and complicates the design and optimization of data centers.

## 4. ENERGY EFFICIENCY METRICS AND DATA CENTER MONITORING

Energy efficiency metrics of the data center are the guideline for the IT managers to operate data centers with high-energy efficient and economical manner. Metrics may be used for self-improvement, comparison to other data centers, improve operation in the data center, site selection or design and assist in selection of a hosting data center (Patterson 2012, p.241). In this chapter, the most common energy efficiency metrics are presented. The most widely used energy efficiency metric in data center industry is power usage effectiveness (PUE). Energy reuse effectiveness (ERE) is an extension of PUE and takes into account utilized waste energy. Data center monitoring is an important tool for design and control data centers, and proper monitoring is a requirement for the efficiency metric calculations.

### 4.1 Basic data center metrics

General target for metrics is to measure and improve some value function or parameter. The simplest data center metrics are power/area, power/rack, cost/area and cost/power. These basic metrics have been used for a long time, but their usability is restricted. (Patterson 2012, p. 245)

Power/area gives an overall power density for the data center. It is the most frequently used metric. It can be used on the large scale, as the utility or central cooling plant sizing, but in smaller scale it is not adequate. Data center power density can vary considerably across the room, so it is not possible to use value of power/area to design specific cooling or power architectures. It only gives average of data center power density. More important and precise power density metric is power/rack, as same data center may have racks between 2 kW to 20 kW. Providing power and cooling to these racks, may require different solutions. (Patterson 2012, p. 245)

Basic metrics to compare the costs of data centers are cost/area and cost/power. Power/area and cost/area are misleading and those should not be used. Better metric is cost/kW of connected IT load, which takes into account layout efficiency and room power density. (Patterson 2012, p. 246)

### 4.2 Power usage effectiveness (PUE)

PUE is the efficiency metric which has become a standard in data center industry over time and is the most commonly used metric for reporting energy efficiency of data centers

(Brady et al. 2013). PUE was promoted by the non-profit organization of IT professionals, Green Grid, in 2007. It is defined as follows (The Green Grid 2007) :

$$PUE = \frac{\text{Total facility energy}}{\text{IT equipment energy}} \quad (1)$$

Equation (1), IT equipment energy consists of energy associated with all of the IT equipment (e.g., servers, network and storage equipment) and supplemental equipment which are used to control the data center. Total facility energy consists of all IT equipment energy plus all energy required to support the data center such as energy used to cool data-center, power delivery components, and other miscellaneous component loads, such as lighting and security system. Cooling system consists of a chiller plant, CRAHs, CRACs, fans and pumps. Power delivery include UPS systems, switchgear, generators, PDUs, batteries and energy lost in power distribution and conversion. (The Green Grid 2007)

Cooling system architecture, local climate, the availability of geothermal sources, duration and frequency of the measurement affects all the PUE value of data center, and therefore comparing PUE values of different data centers demands great precision. Typical values ranges from PUE = 2.7 for a traditional raised floor data center, 1.7-2.1 by applying additional in-row cooling and containment, to PUE =1.3 using advanced containment methods like rear door heat exchangers. Lower values are attained with advanced cooling systems and utilizing geothermal energy. (Garimella et al. 2012)

In the most rigorous form of PUE, values used for reporting PUE should be an annual basis online measured values tracking all of the energy inputs. Even though strict definition of PUE is annual average of values, instantaneous values for PUE can also be used, for example, examining influences of free-cooling periods to value of PUE. Both energy and power based calculation of PUE can be beneficial. (Patterson 2012, p. 250)

In a stand-alone data center, calculation is straightforward. If data center is located in the building, which house also other functions, main difficulty of calculating PUE is to determine the energy usage of data center environment. Total energy use must be apportioned for the data centers and other users, and energy used by IT equipment must be distinguished from total facility energy. (Avelar et al. 2012)

Straightforward method to apportion cooling energy is to divide energy demand based on chilled water flow rates ( $\dot{V}$ ). More accurate values are received using also temperature differences ( $\Delta T$ ) to apportion and divide energy demand based on thermal power ( $\dot{Q}$ ) carried to different part of the building, based on equation (2).

$$\dot{Q} = \dot{V} \rho c_p \Delta T, \quad (2)$$

where  $\rho$  is the density of water in average temperature,  $c_p$  is specific heat capacity of water and temperature difference is calculated from inlet ( $T_{in}$ ) and outlet ( $T_{out}$ ) temperatures of cooling water,  $\Delta T = T_{out} - T_{in}$ . To get the annual energy use, flow rates and temperature difference must be integrated over the entire year. (Avelar et al. 2012)

When PUE is calculated only for a section of a data center's infrastructure, it gives partial power usage effectiveness (pPUE). Value of pPUE can be used for optimizing a subsection of a data center over time or comparing two identical spaces that are supported by a common central infrastructure. (Patterson 2012, p. 249)

It should be pointed out that PUE is not a superior metric. It is a capable tool for infrastructure improvements but it does not take into account efficiency of power use in ITE properly. For example, replacing older servers with newer, more capable and less energy using servers, PUE can rise. (Patterson 2012) Generally, efficiencies improve with load, so performance impact should be taken into account on a metric but in PUE it is not included (Kant 2009). Brady et al. (2013) made a critical assessment of calculating PUE and listed some problems concerning PUE. Correct calculation demands annual values of several parameters but such extensive monitoring is not widely used. Calculation of PUE is rarely transparent because of strict privacy measures of companies and this made direct verification and repeatability of calculations difficult. Overall conclusion about PUE in the article was that it is good that company follows its energy consumption with some metric, but when compared to other locations, value tells more about climate than a real effectiveness of the data center.

### 4.3 Energy reuse effectiveness (ERE)

Because PUE has been widely used, it is also misused and application may be in conflict with the original definition and calculation method of PUE. One specific situation is when data center waste energy is reused in a facility and PUE is claimed to get values less than 1. To resolve this, The Green Grid defined a new metric, energy reuse effectiveness (ERE), to account for energy reuse. (The Green Grid 2010)

$$ERE = \frac{\text{Total energy} - \text{reused energy}}{\text{IT energy}} \quad (3)$$

A theoretical ideal value of ERE is 0 and if no energy is reused, the value of ERE is the same as the value of PUE. Same ERE value can be achieved with originally low PUE and with high PUE and wide reuse of energy. Reporting both values, tells more about effectiveness of the data center. (Patterson 2012, p. 254)

### 4.4 Component metrics

Metrics for data center components and subsystems represent the efficiency of the component as installed but they do not provide overall sight for data center efficiency

model. Those are informative and give broader understanding of the overall efficiency chain. (Patterson 2012, p. 261)

Efficiency of a chiller can be approximated with COP. Airflow from data center airflow units divided by the power to move it tells efficiency of airflow units. Ratio of total room supplied airflow to the total IT required airflow is a metric for total room airflow efficiency. Rack cooling index provides the percentage of the servers in a given rack that are below (or above) recommended maximum (minimum) temperature and hence scores airflow distribution within the data center. (Patterson 2012, p. 262)

Fans of IT equipment and the quality of the server thermal management system can be evaluated with the flow rate of the internal fans divided with the power dissipation (the cooling load) of the server. Also IT power conversion efficiencies affect to the overall data center efficiency. (Patterson 2012, p. 263)

## **4.5 Data center monitoring**

Data center monitoring, both IT and facility, is the key to solve problems such as device placement, capacity planning, equipment maintenance, failure and downtime, energy efficiency and utilization in a data center. IT side of data center is already well monitored and its importance is well understood. Facility monitoring is as important, and combining IT and facility monitoring several difficulties can be solved. (Bhattacharya 2012, p. 200)

Both the data center cooling and the power distribution systems require comprehensive monitoring solutions combining real-time and historic information to ensure energy optimization, performance, reliability and security in a data center. Proper monitoring also enables automation of a data center and cooling system operation. For the optimization of a cooling system, the data of the chillers, IT equipment inlet and outlet temperatures and airflow, humidity control, CRAC/CRAHs, and ambient air are needed. For the optimization of the data center power distribution system, values are monitored from the building meter, transfer switch, generator, UPS, PDU and IT equipment. (Bhattacharya 2012, p.203-220)

Most of the variables of data center have hourly, daily, weekly, monthly and seasonal variance. The more frequent measurements are provided, the more accurate data set to analyze is achieved. Continuous real-time monitoring with data captured every 15 minutes or less is recommended by the Greed Grid. If real-time monitoring is not possible, process to capture desired values should be repeatable, defined, and as often as possible. (Avelar et al. 2012)

Data collection and management, in the scale as presented above, is challenging because proper software tools for monitoring are still rare. There is a software, which can collect facilities data, but not IT data, and other way round. Some software tools are restricted to

specific platforms. Often custom applications need to be built at every site. And when adding the fact that data center is a dynamic environment, implementing and maintaining a data center monitoring system is a challenge. (Bhattacharya 2012, p.231)

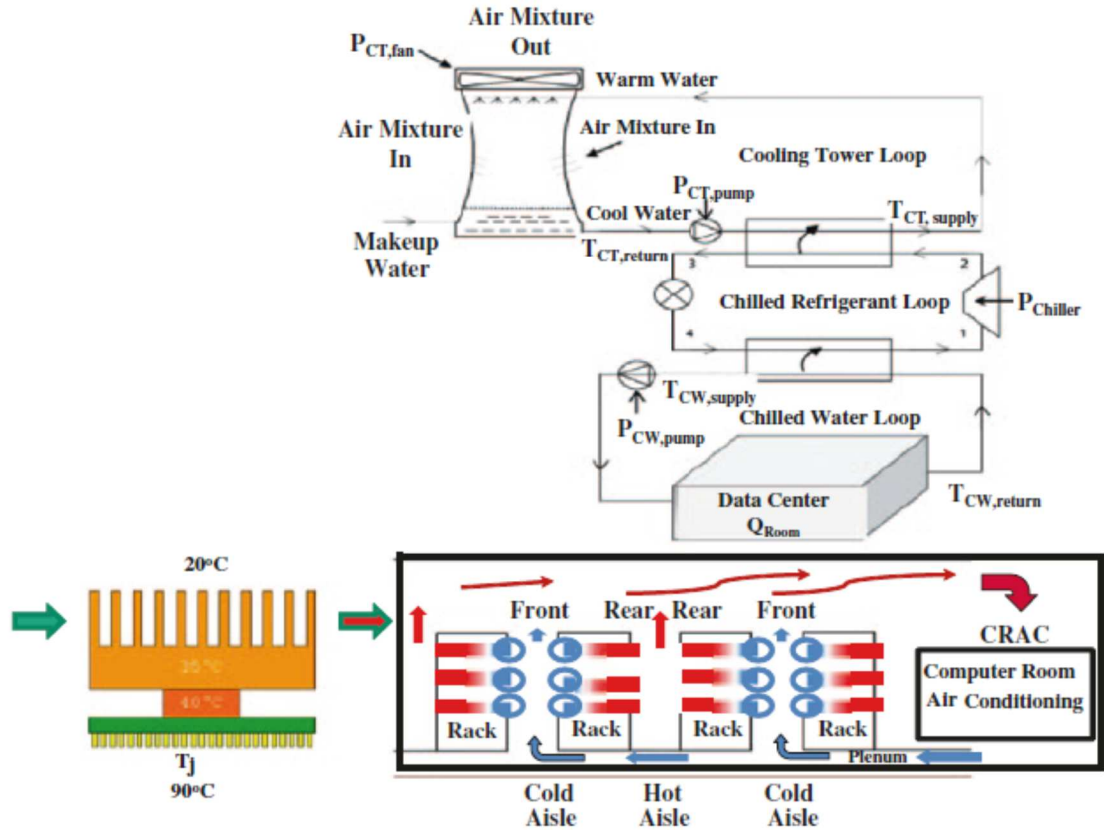
## 5. DATA CENTER COOLING

Heat transfer from the chip to ambient consists of multiple heat transfer interfaces and cycles. To enhance energy efficiency, all possible intermediate interfaces should be eliminated. Even there is multiple techniques and coolants in use, yet there is no single coolant or technique to cover the entire cooling process from chip to ambient. (Garimella et al. 2012) In this chapter, different techniques to carry out data center cooling are presented. Air cooling has been predominant technology but as power and cooling demand have increased, capability of air cooling has exceeded. Close liquid cooling, direct liquid cooling and two-phase cooling are introduced as an alternative to the traditional air cooling.

### 5.1 Traditional air cooling

Majority of data centers use air cooling systems to maintain desired operating conditions in a data center. Typical air cooling configuration and various resistances between the heat source and the sink are presented in Figure 3. Heat generated by the processor conducts to a heat sink and further to the cooling air blowing into the server. Cooling air to the data center is supplied and drawn by CRAC or CRAH where air is cooled by chilled water. Cooling water is cooled down in a chiller. (Dai et al. 2014) Air cooling is typically preferred because of its wide usage in computer cooling, proven high reliability, and lower initial and maintenance costs compared to other cooling methods (Ohadi et al. 2012).





**Figure 3. Traditional air cooling with the various resistances (Dai et al. 2014).**

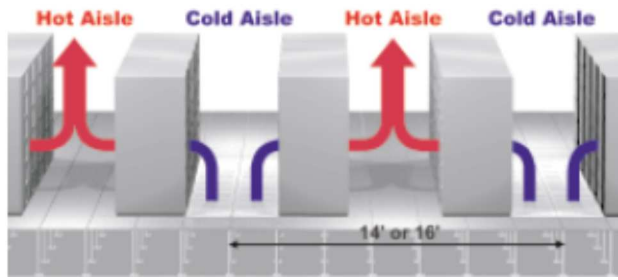
As can be seen in the Figure 3, cooling system contains several thermal resistances. Most significant thermal resistances are between the processor and the heat sink, and between the heat sink and the cooling air, and these resistances have been actively researched. Direct heat removal from electronics with advanced heat sinks and high-conductivity thermal substrates enhance heat removal from the processor to the heat sink. Air side heat removal has enhanced with many augmentations. (Dai et al. 2014)

In traditional air cooled data center, the most common design is a raised-floor data center, in which air is supplied through a raised and perforated floor. In raised-floor data centers, the server racks are installed on a tile floor that is raised 0.3-0.6 m above the solid floor. CRAC/CRAHs pump cold air to an under floor plenum and further to servers through perforated tiles or grilles. Raised-floor arrangement is flexible and allows to supply cooling air to each rack. Flow field and pressure variation under the raised floor are the key to the proper distribution of cooling air to the racks. (Patankar 2010)

Option to raised-floor is a hard floor data center. For example, retrofitting and load capacity of the tile floor may restrain its use. Hard floor data centers cooling air may be distributed by upflow CRAH units, overhead ducts and advanced cooling solutions (Patankar 2010). As raised-floor data center design is predominant in the industry, research is focused mainly on that configuration.

Srinarayana (2012) et al. made computational comparison between hard floor and raised floor cooling configurations. They compared different room and ceiling return strategies and concluded that using a ceiling return for hot exhaust air gives better thermal performance than room return, for both hard-floor and raised-floor configuration. They also observed that hard-floor with overhead supply-return strategy gave the best thermal performance as raised-floor data centers typically have under-floor plenum obstructions limiting flow rate through perforated tiles and causing hot spots.

Two issues in air cooled data center are the air bypassing and the mixing of warm and cold air (Ohadi et al. 2012). Air flow management, as presented in Chapter 3.3, deals with these issues. To prevent the mixing of warm and cold air and warm air exhausted by one rack entering the inlet of another rack, racks in data center are often arranged in hot and cold aisles, as Sullivan (2002) has originally proposed and presented in Figure 4. The server racks are placed on both sides of the cold aisle so that their inlets face the cold aisle and rear to the hot aisle, exhausting hot air to the hot aisle. Hot and cold aisles can be further separate using curtains or hard partitions to form hot or cold containments (Dai et al. 2014) .



**Figure 4. Alternating hot and cold aisle arrangement of racks in a data center (Sullivan 2002).**

In an air-cooled data center, air distribution has a significant role for cooling performance of the data center. Power demand of transporting cooling air to and from servers,  $P$ , can be calculated with Equation (4) based on the Bernoulli equation. Fan's power,  $P$ , is dependent on pressure difference over the fan,  $\Delta p$ , volume rate of air,  $\dot{V}$ , and efficiency of a fan,  $\eta$ . All the elements of this equation should be studied when object is to decrease energy consumption of fans.

$$P = \frac{\Delta p \dot{V}}{\eta} \quad (4)$$

Flow paths, duct sizes and distribution tiles in a data center affect heavily the pressure needed and hence energy demand of the fans (Brady et al. 2013) as was discussed in Chapter 3.3. If the volume rate of air is larger than needed because of by-pass, energy demand of the fan is also larger.

Iyengar et al. (2010) made a comparison based on CFD analysis, what would be the most effective way to reduce energy usage in data center by controlling the CRAC unit. They found out that use of a motor speed control to ramp down the CRAC air flow rate was the most effective method reducing data center cooling energy demand up to 12,6 % of IT load. Shutting down underperforming CRAC units provided a reduction of 8.1 % of IT load. The least successful method they tested was increasing the refrigeration chiller plant water set point temperature, which reduce cooling energy up to 3.6 % of IT load.

Also potential to enhance efficiency of fans is good. In survey made in Sweden between years 2005 to 2009, it was found that average total efficiency of the fans used in existing HVAC systems was only 33 % (Brelvi 2012) being far beyond the EU regulation on efficiency of fans (EU Directive 2009/125/ECO). Designing and using more energy efficient fans and introducing better control strategies could save 50 % of electricity used to run fans. Direct-driven fans with an electronically communicated motors (EC motors), integrated frequency converter for step-less load control and an impeller with low aerodynamic losses have the best efficiencies. Setting specifications for the fan needs careful consideration, because the real operating point affect remarkable the efficiency and operating of the fan. The affinity law says that reducing speed of a fan saves energy. (Brelvi 2012)

As power and cooling demand of a data center have increased, a limit in capability of air cooling has exceeded. There is two limits, practical limit and theoretical limit. Practical limit becomes from the existing design of a particular data center, being different for every data center. Local room air flow should be compared to vendor-supplied airflow rates required for cooling. If required airflow rates can be reached in data center, limit is based on the server and not the room. Theoretical limit becomes from thermal management of components in the server. There exists already successfully air-cooled racks of 30 kW. (Patterson & Fenwick 2008) For sufficiently cold climate year around, air cooling may continue to be economical and the most preferred option (Ohadi et al. 2012).

## **5.2 Close liquid cooling**

Liquid cooling of server racks can be implemented with several methods. There is rear-door heat exchangers, in-row coolers, overhead liquid coolers, and closed-liquid coolers. Heat exchangers of rack level liquid cooling are normally connected to the house's liquid cooling system.

Server rack can be equipped with liquid-cooled door (rear-door cooling) which cools down the air flowing through the servers before return to data center ambient. Water cooled rear door heat exchangers are widely utilized in racks dissipating over 20 kW (Joshi & Kumar 2012, p.589). Similar to the liquid cooled doors are in-row liquid coolers and overhead liquid coolers, which remove the heat near the heat sources but there is still local room airflow. An in-row cooler is replacing one rack in the middle of a rack row

and it draws in hot air from hot aisle, internally cools it, and exhaust cold air into the cold aisle (Patankar 2010). The advantage of in-row coolers and overhead liquid coolers is that they are not limited to a specific server or rack manufacturer (Patterson & Fenwick 2008).

Closed liquid cooled rack is another method in which the rack is sealed so that airflow is fully contained within the rack and air is cooled with heat exchangers inside the rack. Racks are thermal and airflow neutral to the room, and usually also quiet. Closed liquid cooled rack need to be equipped with mechanism which opens the rack door to prevent overheating in case of a failure in cooling. (Patterson & Fenwick 2008) Opening the racks' doors does not alone solve the problem of overheating since also ambient temperature of data center raises rapidly if cooling liquid cycle in the room is interrupted and heat load of the racks is large.

Smart cooling solutions are one way to achieve energy savings. In rack-level cooling, variable-speed fans modulated by temperature measurements, may replace server level fans which are normally small, high-velocity fans causing noise problems (Kant 2009). Energy costs of air distribution with small, on-board fans are normally included in part of the IT load instead of total energy consumption. It leads to the situation that PUE is larger if large fan units are used than with small on-board fans even though total energy consumption is reduced with large fans (Brady et al. 2013). With close liquid cooling, higher heat dissipating rates per rack is allowed, so needed space is smaller and savings of rental costs are achieved. (Joshi & Kumar 2012, p. 592)

### **5.3 Direct liquid cooling**

In the direct liquid cooling, heat-generating components as microprocessors are in thermal contact with cold plates with circulating coolant. Coolant, which can be in a single-phase or change phase, is circulating using a pump or passively utilizing natural convection. Cold plates with internal cooling are normally metal and have internal coolant passages, allowing a large heat transfer surface area with a low pressure-drop. Heat from microprocessors is rejected to the ambient air or to another liquid stream. (Joshi & Kumar 2012)

With direct liquid-cooling, two of the least effective heat transfer processes of data center cooling can be eliminated: heat-sink-to-air and air-to-chilled-water (Ohadi et al. 2012). Thermal resistance of liquid cooled systems, where heat removal capacity is more than  $200 \text{ W/cm}^2$ , is less than 20 % of the thermal resistance in air-cooling systems (Ebrahimi et al. 2014).

Choice of the cooling liquid is problematic. Water has good thermal properties and it is safe and cheap, but it damages electronics if leaks occur. Dielectric liquids are electronic-friendly but they have poor thermal properties in the single phase and are expensive. Ammonia may be an optimum working fluid but it has several safety risks. (Ohadi et al. 2012)

Based on CFD simulations made by Ohadi et al. (2012) using water as a cooling fluid, inlet temperature for water could be about 62 °C and for dielectric fluid such as R-134a it should be -4 °C. Thus use of water or other high performance fluid as a cooling fluid do not need a compressor but for a dielectric fluid it is needed.

Chi et al. (2014) made an energy and performance comparison between an advanced hybrid air-water cooled data center and enclosed, immersed, direct liquid-cooled data center. Comparison was based on values which were collected from real operational systems and converted to 2 hypothetical equivalent systems to enable a detailed comparison. Air-water cooled system used rear door liquid-loop heat exchangers connected to large scale chillers. Liquid-cooled solution used natural convection properties of the fluoro-organic dielectric coolant for heat transfer from the microelectronics to the water jacket. The result was that fully immersed liquid-cooled solution is able to achieve a partial PUE of around 1.14 at full load when it was 1.48 for equivalent air-water hybrid system. Partial PUE of air-water cooled system was calculated for the case where IT system were fully loaded and free-cooling of a chiller was not used. It is also observed that in a water cooled system, processor performance can be increased by 33 % compared to air cooled system (Ebrahimi et al. 2014).

Chi et al. (2014) have listed advantages and disadvantages of direct liquid cooled systems. Higher heat transfer capacity per unit gives the biggest advantage against the air cooled systems. To carry specific amount of heat, large volume of air is needed resulting high speed. When utilizing density driven natural convection, the fluid velocity is very low and high heat transfer capacity is needed. A liquid-cooled data center also requires fewer fans and rotating components. This leads to the smaller energy consumption, lower noise level, and increased reliability as there is less moving parts. Computer nodes will be inside a sealed container and environment is fully controlled, and problems caused by dust, vibration and elevated temperature are negligible. Major disadvantage is in ensuring liquid sealing and avoiding leakage problems. As coolant is normally not water, leakage is dangerous for both personnel and equipment. To verify correct specification and management of pumps, pressure variation within liquid system ( $\pm 0.5$  atm) need to be realized. On-chip cooling needs also significant number of tubing connections and system must allow individual servers to be taken in and out of a rack (Ohadi et al. 2012). Higher temperature levels of liquid cooling can eliminate the need of chillers and provide higher quality waste heat (Ebrahimi et al. 2014).

## 5.4 Direct two-phase cooling

The need of effective cooling solution for devices with energy loads more than 1000 W/cm<sup>2</sup>, is one motivator to implement two-phase cooling systems in data centers. Nucleate boiling increases convection heat transfer coefficients and enables heat flux to be from 790 W/cm<sup>2</sup> to 27 000 W/cm<sup>2</sup> when effective heat sinks are used. (Ebrahimi et al. 2014) Ohadi et al. (2012) have also analyzed potentials of direct two-phase cooling, and made

a comparison between air, liquid, and two-phase cooling, which can be seen in Table 2. Direct two-phase cooling makes possible to eliminate the use of chilled water and HVAC equipment to sub-cool the cooling water. This needs low thermal resistance of the cold plate. For example, thin film manifolded microchannels can be used. Their thermal resistance can be as low as 0.04 K/W compared to commercially available cold plates (0.15 to 0.20 K/W). If thermal resistance is low enough, heat from the chip can be rejected to the ambient using only refrigerant loop with evaporation on the chip side and condensing of the refrigerant in an air-cooled condenser. Based on CFD simulations mentioned a previous chapter, inlet temperature of two-phase flow (R-245fa) can be as high as 76.5 °C. This high temperature level enables waste-heat recovery. Thin film manifolded microchannels provide an order of magnitude higher heat transfer coefficients than two-phase flow with traditional cold plates. Same advantages as in direct liquid cooling can be associated for two-phase on-chip cooling. Additionally advantages of two-phase cooling are that compressors, fans and heat exchangers are not needed anymore, amount of cooling fluid to be pumped is reduced, and capital costs, operating costs, real estate and building expenses are lower.

**Table 2. A comparison between air, liquid, and two-phase cooling (Ohadi et al. 2012).**

	Air	Water	Dielectric fluid (FC-72)	Two-phase flow R-245fa
<b>Generated power (W)</b>			85	
<b>Fluid inlet temperature (°C)</b>	5	62.4	-4	76.5
<b>Thermal resistance (K/W)</b>	0.4-0.7	0.15-0.2	0.15-0.2	0.038-0.048
<b>Pumping power (mW)</b>	29	57	56	2.3

Ebrahimi et al. (2014) made a comparison of waste heat technologies and their suitability for integration with air-cooled, liquid cooled and two-phase cooled data centers. Temperature levels of waste heat for liquid cooled systems were considered to be 60 °C and for two-phase cooled systems 75 °C, which provide higher quality waste heat streams and enables also greater variety of possible waste heat reuse scenarios compared to air-cooled systems, in which temperature levels are lower (45 °C or less). Based on the comparison the most promising and economically beneficial technologies for data center waste heat reuse were found to be absorption refrigeration and organic Rankine cycle. Standard vapor compression refrigeration cycle can be replaced by the absorption refrigeration system, in which a liquid solution of absorbent fluid and refrigerant is used instead of a vapor compression system. With organic Rankine cycle, waste heat from data centers can be converted to electricity on-site. The organic Rankine cycle works on the same basis as

the steam Rankine cycle, but instead of steam it uses organic fluids as a working fluid because organic fluids have lower boiling points than water.

## 6. FREE COOLING

Traditional vapor compression cooling systems consumes energy all year round, even at night and in winter when temperature is low. Free cooling exploits natural cold source to cool data center in economical, ecological and sustainable way. Economizers can be used to utilize outdoor air or natural cold water, and under favorable conditions, the compressor can be bypassed. Among economizers also heat pipe method has a great application potential. Free cooling methods, presented in this chapter, are categorized in three categories: airside free cooling, waterside free cooling and heat pipe free cooling. These methods and their subclasses are gathered in the Table 3. (Zhang et al. 2014)

Strict environmental demands of data centers have been a barrier to utilize free cooling at the extent it would have been possible (Zhang et al. 2014). Now the 2011 ASHRAE classes A3 and A4 for data centers, as presented in Table 1, expanded the environmental envelopes for IT equipment and brought a good opportunity for free cooling. Utilizing free cooling is considered to be one of the most prominent ways to enhance energy efficiency of data center (Malkamäki & Ovaska 2012).

**Table 3. Different types of data center free cooling systems (Zhang).**

Category	Type	Feature
Airside free cooling	Direct	Drawing the cold outside air directly inside
	Indirect	Utilizing the outside air through heat exchangers
Waterside free cooling	Direct water cooled	Using natural cold water directly
	Air cooled	Using air cooler to cool the circulating water
	Cooling tower	Using cooling tower to cool the circulating water
Heat pipe free cooling	Independent	With no mechanical refrigeration function
	Integrated	Integrated with mechanical refrigeration system
	Cold storage	Combined with cold storage system

### 6.1 Airside free cooling

Acceptable values of data center environment are normally based on recommended operating ranges given by the standards and/or industry guidelines. If ambient air conditions outside are within this range, or if outside air can be mixed with warm return air to meet the range, outside air can be used for data center cooling via an air-side economizer fan. To meet recommended operating range, a chiller and humidity control system could be implemented. (Ohadi et al. 2012) The outside air can be used either directly in the data



center or indirectly by air to air heat exchangers (Zhang et al. 2014). Even 99 % of locations in Europe can meet the ASHRAE's Thermal Guideline A2 allowable range (as presented in Table 1) using airside economizer cooling all year round (Harvey et al. 2012).

Drawing the cold outside air directly into the data center is the simplest free cooling method. Airside economizer consist of a system with controls, dampers, and fans. Many IT companies have constructed their data centers with direct airside economizers. Direct airside free cooling does not require pump, cooling tower, or any steps of heat transfer. (Zhang et al. 2014)

Free air cooling is naturally available and is an inexpensive option, but it poses several operating environment challenges, for example elevated temperature variation, wider humidity range and contaminants. These challenges are dealt with the operators, regulators, equipment suppliers and standard communities. Thermal cycling and elevated temperatures are likely to be higher in a free air cooling system which may reduce long term reliability of IT equipment. Humidity range may be wider and favorable for the corrosive failure mechanisms. When free air cooling is used, various reactive gases from outside can enter to the data center, and they can interact with metals and accelerate various failure mechanisms, especially together with high humidity. In addition, particles of different sizes and densities may accelerate several other failure mechanisms. (Ohadi et al. 2012) The risk of direct airside free cooling depends greatly on the local environment (Zhang et al. 2014).

Indirect airside free cooling does not disturb the internal environment of data center as direct airside free cooling. Indirect airside free cooling uses air to air heat exchangers to cool data center with ambient air. Problems for these heat exchangers may come from contaminants which air contain. Those will accumulate over time, reduce heat-transfer coefficient and increase maintenance need. Other disadvantage is the size of the heat exchanger. Surface area for heat transfer need to be large to maintain required heat transfer and acceptable pressure drop. (Zhang et al. 2014)

Depending on weather conditions outside, airside free cooling without additional cooling may results in higher operation temperature in the data center. To compensate higher temperature of cooling air, larger volume of air needs to be circulated through the data center and thus larger or more fans are required (Kant 2009). Energy needed for moving larger volume of air should be compared to the energy savings of decreased number of CRAC units.

## **6.2 Water side free cooling**

Waterside free cooling use natural cold source through a cooling water infrastructure. Internal environment of a data center is not disturbed, and waterside economizers are more cost effective than the alternative airside economizers. Waterside free cooling can

be divided into three types: direct water cooled systems, air cooled systems and cooling tower systems. (Zhang et al. 2014)

Direct water cooled system uses cold water from sea or lake directly to cool the data center. Closed cooling water loop brings heat from data center and transfer it through a heat exchanger to natural cold water. If natural cold water is available, direct water cooled system is efficient and can maintain a temperature close to the average ambient temperature for 24 h per day. (Zhang et al. 2014) District cooling can be seen as a direct water cooled system.

In an air cooled system, closed cooling water loop is cooled in a dry cooler when outside temperature is low enough. Dry cooler can be implemented in a direct expansion chiller or CRAC. (Zhang et al. 2014)

In a cooling tower system, a cooling tower is used to cool cooling water loop. When outside air conditions are within specific set points, a chiller can be bypassed and cooling tower can be used for cooling. When the heat exchanger is in series with the chiller, partial operation is also possible. This system is widely used in large-scale data centers and it brings significant energy savings. Cooling tower free cooling system is also possible to combine with absorption refrigeration, in which solar energy or waste heat of data center is utilized. This combination has a good application potential. (Zhang et al. 2014)

### **6.3 Heat pipe free cooling**

Heat pipe systems have good temperature control features and ability to transfer heat at small temperature difference without external energy. Heat pipe free cooling system can be divided into three types: independent system, integrated system, and cold storage system.

Independent heat pipe system can only cool a data center by heat pipe and therefore it needs a supportive vapor compression system when the ambient temperature is high. An integrated system combines heat pipe and air conditioning system.

Because cooling capacity of heat pipe systems depends greatly on the ambient temperature, it is not stable and reliable cooling system to use alone. Heat pipes combined with a cold storage system can overcome these drawbacks. During daytime when the ambient temperature is higher than inside, heat dissipated from the equipment are stored in the thermal energy storage unit as a sensible heat in water and a latent heat in phase change material. During night time, stored heat is transferred to the ambient by the thermosyphons. This is efficient system especially for remote areas where there is no power grid and the maintenance is limited.

## 7. RISKS AND RELIABILITY

Cooling strategy and growing heat loads of a data center have also influences on safety and reliability of the data center. Health and safety risks, and reliability are briefly discussed below.

### 7.1 Health and safety risks

When equipment power densities in a data center increase, several health and safety issues may come up. Temperature and noise levels may be higher. When energy efficiency is improved by preventing mixing of cold and hot air, for example using cold and hot aisle containment, air temperature in a hot aisle is increased and affects personnel working conditions. Fink (2005) points out that more realistic meter to describe heat stress effect of the operator would be the wet bulb globe temperature (WBGT), where also relative humidity and radiation is taken into account, instead of commonly used dry bulb temperature. He has examined the difference in a hot aisle WBGT of the data center with and without hot aisle containments, and difference was found to be small (only 0.5 °C higher for containment system).

Also surface temperatures are raising because of increasing compactness and functionality of electronic devices and thus producing potential health risk. Roy (2011) has listed lacks in safety criteria concerning surface temperatures provided by industry and government organizations and demanded more explicit methods to set safe product temperatures. Criteria is normally based on temperature of material and not on skin contact temperature. Standards use also constant and uniform surface temperatures and do not take into account possible hot spots. Material categorizing and contact times are not exactly specified. These facts may lead significant over- and under-estimation of surface temperatures. For example, as thermal properties of some polymers are same as those of metals, categorizing materials in three groups (metals, ceramics/glasses and plastics/insulators) with one specified limit per group, may lead safety hazards.

Noise levels are also increasing because of larger cooling flow rates needed in energy intensive data centers. Also air inlet temperature raise of a server affects data center acoustic noise level. (Joshi & Kumar 2012, pp. 605) ASHRAE (ASHRAE TC 9.9 2011) has presented empirical fan law which predicts sound power level being proportional to the fifth power of the fan rotational speed. Noise level of the standard configuration data center is about 85 dB with 25 °C air inlet temperature. If temperature is increased to 30 °C noise level would be about 89.7 dB. When noise level exceed 85 dB, hearing protection is mandatory (L 23.8.2002/738). With advanced cooling methods, as close liquid

cooling, and direct liquid and two-phase cooling, noise levels can be reduced, since multiple fans per server used in air-cooling are not needed (Ohadi et al. 2012).

## 7.2 Reliability

Data centers are operated 24 hours per day all the year round. Any unexpected downtime in the operation of the data center is waste of time, money and information. Power distribution in data centers and its facilities must be reliable in every situation. It is verified with backup power and cooling systems. (Energiatehokas konesali) Uptime Institute has created the standard Tier Classification System to consistently evaluate data center facilities as potential site infrastructure performance, or uptime. Four categories as called tier levels and fundamental requirements of each level are gathered in following table.

**Table 4. Tier classification by Uptime Institute (Explaining the Uptime Institute's Tier classification system).**

<b>Tier I</b>	A Tier I data center provides dedicated site infrastructure to support information technology beyond an office setting. Tier I infrastructure includes a dedicated space for IT systems; an uninterruptible power supply (UPS) to filter power spikes, sags, and momentary outages; dedicated cooling equipment that will not get shut down at the end of normal office hours; and an engine generator to protect IT functions from extended power outages.
<b>Tier II</b>	Tier II facilities include redundant critical power and cooling components to provide select maintenance opportunities and an increased margin of safety against IT process disruptions that would result from site infrastructure equipment failures. The redundant components include power and cooling equipment such as UPS modules, chillers or pumps, and engine generators.
<b>Tier III</b>	A Tier III data center requires no shutdowns for equipment replacement and maintenance. A redundant delivery path for power and cooling is added to the redundant critical components of Tier II so that each and every component needed to support the IT processing environment can be shut down and maintained without impact on the IT operation.
<b>Tier IV</b>	Tier IV site infrastructure builds on Tier III, adding the concept of Fault Tolerance to the site infrastructure topology. Fault Tolerance means that when individual equipment failures or distribution path interruptions occur, the effects of the events are stopped short of the IT operations.

Data center infrastructure costs and complexity increase with Tier level, as do also availability. But as Tier level increase, energy efficiency goes down, because of duplicate components and distribution systems. Each data center is unique, and it is optimization between cost, energy efficiency, and availability of the data center when choosing a Tier level target. Tier level should be always based upon the purpose of the data center. (Patterson 2012, p.266)

Reliability of the data center is not only dependent of facilities of the site but also reliability of society including infrastructure, electricity grid, and regulations. Nordic countries have gained their position as a tempting data center location over the last few years. Reasons are cold climate and low energy costs, a reliable electricity grid, a strong local infrastructure and plenty of space available (Radhakrishnan 2014). At the 2013 Data center risk index, Nordic countries are ranked in top ten (Denmark was not included in the comparison). Many companies have located their data center in Nordic countries including Google, Microsoft, Facebook and Yandex (Radhakrishnan 2014).

## 8. CASE STUDY: EVALUATION AND OPTIMIZATION OF DATA CENTER POWER USAGE EFFECTIVENESS

Main issue of the case study was to evaluate power usage effectiveness (PUE) calculations and enhance energy efficiency of cooling in data centers located in Finland. Examined area consisted of several data center rooms, which are at the basement of two office buildings called A and B.

PUE is an important and regularly monitored metric in industry, and thus it was used PUE as an indicator for the influence of energy efficiency changes.

### 8.1 Cooling system

In the case study, cooling of a data center was arranged with 8 chillers, which provided cooling water to air conditioning, ventilation and CRAHs (computer room air handler). 6 of the chillers with free-cooling function located on the roof of buildings and 2 on the ground level.

In the building A, there was 3 chillers and corresponding cooling water cycles, called C1, C2 and C3. Chiller C1 provided cooling water for the fan coil unit network, which served data centers, and for the air duct cooling of offices. Chiller C2 provided cooling water only for the fan coil units of data centers. Chiller C3 was used only during summer, mainly for office cooling and approximately 10 % for data center cooling. In the building B, there was also 3 chillers and corresponding cooling water cycles, called C4, C5 and C6. Chiller C4 provided cooling water to air supply units and fan coil unit network. C5 provided cooling water to fan coil unit network and to air duct cooling of offices. C6 provided cooling water to the CRAHs in the data centers. Chillers C7 and C8 were located on the ground level. Cooling water cycles C7 and C8 were connected after chillers providing cooling water for CRAHs at the both buildings A and B. In the night time, when there was no need for air ventilation in offices, it was assumed that power consumption of chillers was used for data center cooling.

Data center cooling was carried out using CRAHs, fan coil units and perforated cold air pipes. CRAHs used in data centers were mostly front air delivery type delivering cold air at the top and sucking warm air at the bottom. In one small data center room (DC6), CRAHs blew cold air upwards from the top. CRAHs used in data centers were from different manufacturers (Chiller, Emerson, Liebert), and fans of CRAHs were not automatically speed controlled and adjustment was done manually. On the ceiling, there were in some of the data centers, cooling fan coil units manufactured by Carrier. Cooling capacity

of cooling fan coils were 1 kW, 5 kW or 10 kW being regulated by room thermostats. In large data center halls (DC3, 4 and 5) there were also perforated cold air pipes at the ceiling. Moisturizing of air in the winter was carried through these pipes. In smaller data centers, moisturizing were carried out with CRAHs, which had moisturizing unit involved.

When outside temperature was cold enough, chillers were shut down and the cooling water cycle was cooled by free cooling. Fans were circulating air which cooled the glycol-water –cycle, and the glycol-water –mixture flew through a heat exchanger and cooled down the cooling water cycle. Free-cooling was either on or off and it was operated manually. Temperature limit for the free-cooling to turn on was different for each cooling water cycle and depended on the heat load of the cycle being about  $-4^{\circ}\text{C}$  to  $0^{\circ}\text{C}$ . Because change from chiller cooling to free-cooling was made manually, it needed to be done at the beginning of the working day. Change from chiller cooling to free-cooling was quite slow and needed to be monitored intensively during first two hours. Change back to use chiller cooling was faster.

## 8.2 Improvement of PUE calculation

Value of PUE was used in the company as an indicator to compare data center efficiencies in separate units and locations, and to monitor energy efficiency at the own site. As discussed in Chapter 4.2, comprehensive determination of PUE of the data center is demanding, and the company wanted to evaluate calculation method, which was used to determine PUE of the building. Improvement of PUE calculation is presented below.

### 8.2.1 Original equations

PUE was calculated based on Equation (1) separately for buildings A and B hourly. Calculation was based on monitored values of electricity consumption of cooling, ventilation and IT equipment. Originally, PUE-values were collected monthly for both buildings A and B. The company used average value of building's PUE for the monthly reporting.

Total electricity consumption of cooling was measured using electricity consumption of the ventilation engine rooms in both buildings (*HVAC\_A* and *HVAC\_B*). Energy consumption of 5 air handling units (AHU) used for ventilation of offices were also measured, and these values (*AHU1*, *AHU2*, *AHU3*, *AHU4*, *AHU5*) were subtracted from the values of ventilation engine rooms. Energy consumption of chiller C6 was not measured and it was included to equation as a constant value. Power consumption of a chiller C8 (*C8\_1*) and accessories as pumps and condenser fans (*C8\_2*) were measured separately. Also chiller C7 (*C7\_1*) was measured but it was not included in the monitoring system. In calculation, consumption of C7 was approximated to be same as that of C8. Power consumption of lights and fans of air convectors were included to equation as a constant value. Energy consumption of ITE was measured using several meters.

### 8.2.2 Defined equations

For the standard PUE calculation, several changes were made. Governing equations are presented below. In Equations (5)-(8), corrections made are presented with overstrike (deleted terms) and bold (added terms). Changes are explained the following chapters.

Total facility electric power excluding IT equipment electric power for building A ( $P_{Facility,A}$ ):

$$P_{Facility,A} = HVAC\_A_{Night} \text{---} AHU1 \text{---} AHU2 \text{---} AHU3 + C8\_2 + \mathbf{0.5} \cdot (C8_1 + \mathbf{C7_1}) + \mathbf{0.07} * UPS\_A + 70 \text{ kW} \quad (5)$$

Electric power of IT equipment ( $P_{IT,A}$ ) in building A:

$$P_{IT,A} = RK_A + \mathbf{0.93} \cdot UPS_A \quad (6)$$

Total facility electric power excluding IT equipment electric power for building B ( $P_{Facility,B}$ ):

$$P_{Facility,B} = \mathbf{0.8} \text{---} HVAC\_B_{Night} \text{---} AHU4 \text{---} AHU5 + C8_2 + 0.5 \times (C8_1 + \mathbf{C7_1}) + \mathbf{C6} + \mathbf{0.13} \cdot (UPS_B + \mathbf{UPS2} + \mathbf{UPS3} + \mathbf{UPS4} + \mathbf{UPS5} + \mathbf{UPS6}) + \mathbf{20 \text{ kW}} \text{---} \mathbf{100 \text{ kW}} \quad (7)$$

Electric power of IT equipment ( $P_{IT,B}$ ) in building B:

$$P_{IT,B} = RK_B + \mathbf{0.87} \cdot (UPS_B + \mathbf{UPS2} + \mathbf{UPS3} + \mathbf{UPS4} + \mathbf{UPS5}) \text{---} \mathbf{200 \text{ kW}} \quad (8)$$

PUE is then calculated with Equation (9) separately for both buildings.

$$PUE = \frac{P_{Facility} + P_{IT}}{P_{IT}} \quad (9)$$

Energy consumption of air handling units should not be disregard as it was done in original calculation. The reason is that a part of the data center cooling and moisturizing were done by ventilation through perforated cold air pipes and it is difficult to determine, what portion of total ventilation is used in the data centers and what in the rest of the building. In the nighttime, when there was no need for air ventilation in offices, power consumption of chillers was used for cooling of data centers. Nighttime values of energy consumption could be used for PUE calculation. Also IT load was relatively constant around the clock.

Without possibility to distinguish cooling energy used for datacenters and used for offices by monitoring flow rates and temperature difference of all the devices, there is no point to calculate PUE in every 15 minutes as it was earlier done. When nighttime values were used, sufficient period to measure PUE is one day. IT-load should be summed during the day, and for the ventilation room energy consumption, nighttime (10pm-2am) values



should be multiplied by six. Constants in equations should be converted to unit kWh / day. In equations presented here unit is kW.

It have been assumed that half of the capacity of cooling water cycles C7 and C8 were used in building A and other half in B. To verify this assumption, flow rates and temperature differences of devices which use cooling water from this cycle. For the total PUE of building, this assumption does not have any influence. Energy consumption of chiller C6 was approximated to be a constant in the original calculation. Even though, its energy consumption varied from summer time value of 110 kW to free-cooling period value 25 kW. Measuring of chiller C6 electricity power should be added.

Power consumption of lights and fans of air convertors and CRAHs is not negligible but relatively small so that approximation to use constant value gives sufficient accuracy for the PUE calculation. In building A, value can be approximated to be about 70 kW, and in the building B, 20 kW, which were based on the data collected earlier. Total power consumptions excluding IT loads for buildings A and B are presented in Equations (5) and (7).

IT load measuring in building A has been done comprehensively and all the significant values have been measured and taken into account ( $RK\_A$  and  $UPS\_A$ ). Only defect was that UPS losses were not taken into account. Losses were included in IT-load though they should have been part of overall energy load in the numerator. UPS losses have been determined earlier and they were about 7 % of IT load fed via UPS in building A ( $UPS\_A$ ) and about 13 % in building B ( $UPS\_B$ ), which is about the same as in UPSs in data centers DC1 and DC2 determined during this study. New equation to calculate  $P_{IT,A}$  is presented in equation (6).

In building B, there were more defects in IT load measuring. Four UPSs (UPS1, 2, 3 and 4 in DC1 and DC2) were not measured in the system and in calculations, it was used constant value (200 kW) for those. Measuring should be added and included to the system, or this constant should be regularly updated. Also UPS losses should be taken into account in appropriate way as described above (about 13 % of IT load). New equation to calculate  $P_{IT,B}$  is presented in Equation (8).

PUE was calculated separately for the buildings A and B with Equation (9), and average values were used in the monthly reporting. Average does not give correct value for the total PUE when IT loads are not same in the both buildings. Ratios based on IT loads should be used to calculate correct total PUE.

As an example, value of PUE was calculated with original and defined equation in winter during free cooling period and in summer. Data of days 22.1.2015 and 16.7.2014 were used for calculation. Results are collected in Table 5.

**Table 5. PUE-values calculated with original equation and with new equations presented in this chapter. Values are calculated using data of days 22.1.2015 (free cooling, -10 °C) and 16.7.2014 (summer, +25 °C).**

		Free-cooling period		Summer	
		Original	New	Original	New
<b>A</b>	IT-load (kW)	1076	1054	696	674
	Cooling (kW)	85	118	483	466
	Constants (kW)	70	70	70	70
	UPS loss (kW)	0	22	0	21
	<b>PUE</b>	1,14	1,20	1,79	1,83
<b>B</b>	IT-load (kW)	761	781	730	746
	Cooling (kW)	28	66	216	291
	Constants (kW)	100	45	100	120
	UPS loss (kW)	0	55	0	59
	<b>PUE</b>	1,17	1,21	1,43	1,63
<b>Total</b>	<b>PUE</b>	1,15	1,20	1,61	1,72

If we compare results of original and new equations, it can be seen that new equations give 4 – 10 % higher PUE value. The biggest difference comes from UPS losses which were ignored in original equations. It would be good to check what would be the best and the most accurate way to take into account UPS losses. It is interesting that PUE-value of building A is smaller than the value of building B in winter and remarkable larger in summer. The main reason may be a low IT-load. Usually system works most effectively when it is running at its design load. When cooling is manually controlled, it can be oversized for lower IT-load. It should also be noted that in defined calculation for building B, different constants for chiller C6 in winter (25 kW) and in summer (100kW) were used. Difference is possible to take into account only with measuring electricity power of chiller C6.

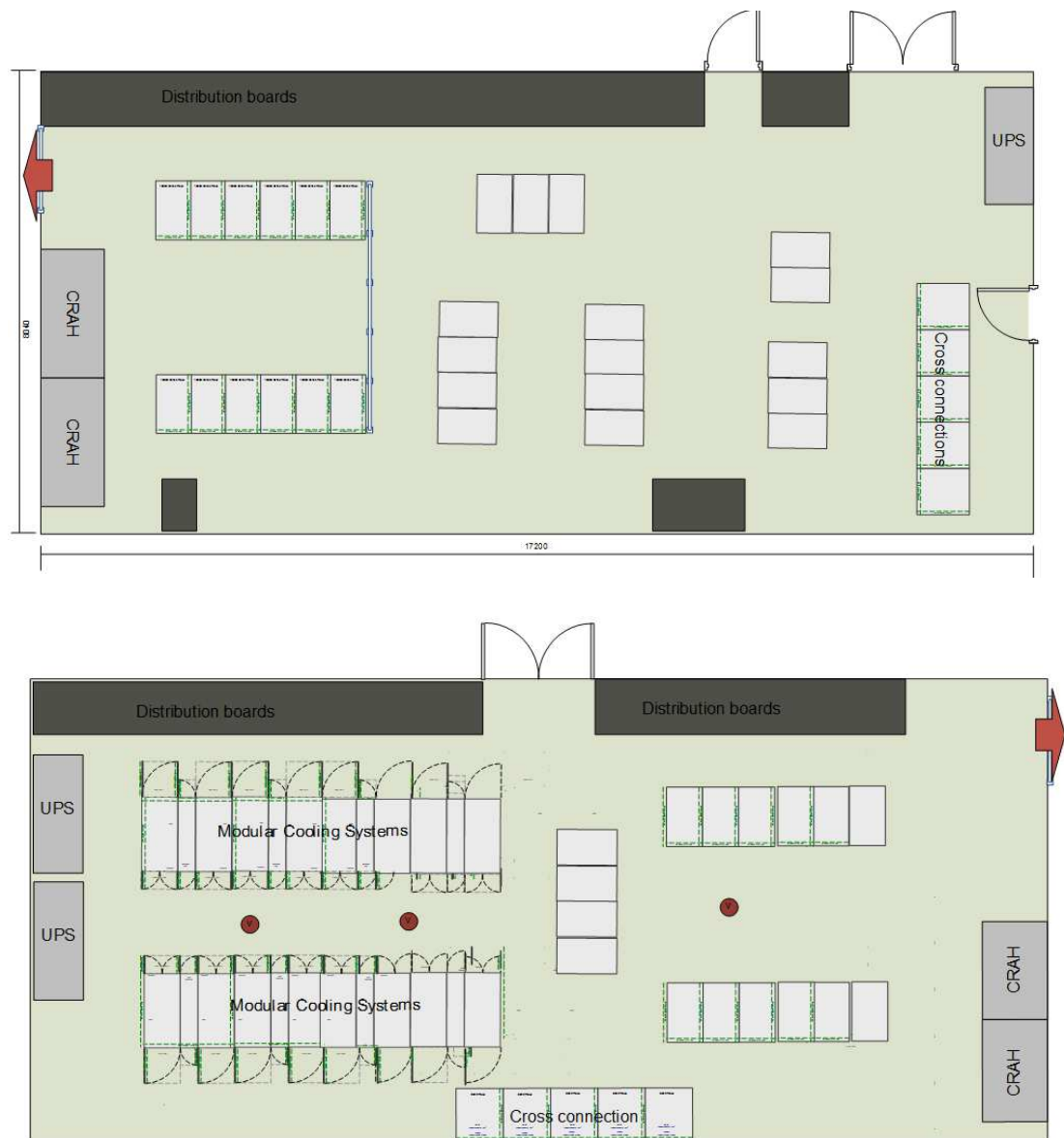
Partial PUE for every data center is not easily achieved. It would need constant flow and temperature measuring in every cooling device and chiller. Also IT-load measuring should be apportioned for data centers. Water cooled racks already give cooling capacity but chiller cooling capacity (flow rate and temperatures) at traditionally air cooled data centers should be measured.

### 8.3 Traditional air cooling compared to close liquid cooling

In the case study, the company wanted to compare the efficiency of close liquid cooled racks to traditional air cooling. To compare traditional air cooling to the close liquid cooling, two identical data centers, DC1 and DC2, were studied. In both rooms, there were four water cooled computer room air handlers (CRAH), two older in separate room and two inside the datacenter. Older ones had steam moisturizing units which were used in

winter time. DC1 was completely air cooled but DC2 had 16 racks with close liquid cooling.

Approximate lay-outs of data centers are presented in Figure 5. Data center DC1 was traditionally air cooled. Racks at the left part of the room and cold aisle between them were separated with the screen. At the rest of the room, racks were not systematically located and no clear hot and cold aisles were formed. In data center DC2, half of the space was filled with 8 water cooled (WC) dual-racks, where cooling water was delivered straight to the dual rack system to cool hot air inside the rack. In the rest of room, there was still some older servers and storages which needed an air cooling. Air cooling capacity in DC 2 was kept almost the same even though heat load has decreased. Water cooled racks needed also some air cooling capacity, because the maximum heat loss of water cooled racks to ambient was 10 % of total heat load of water cooled rack unit.



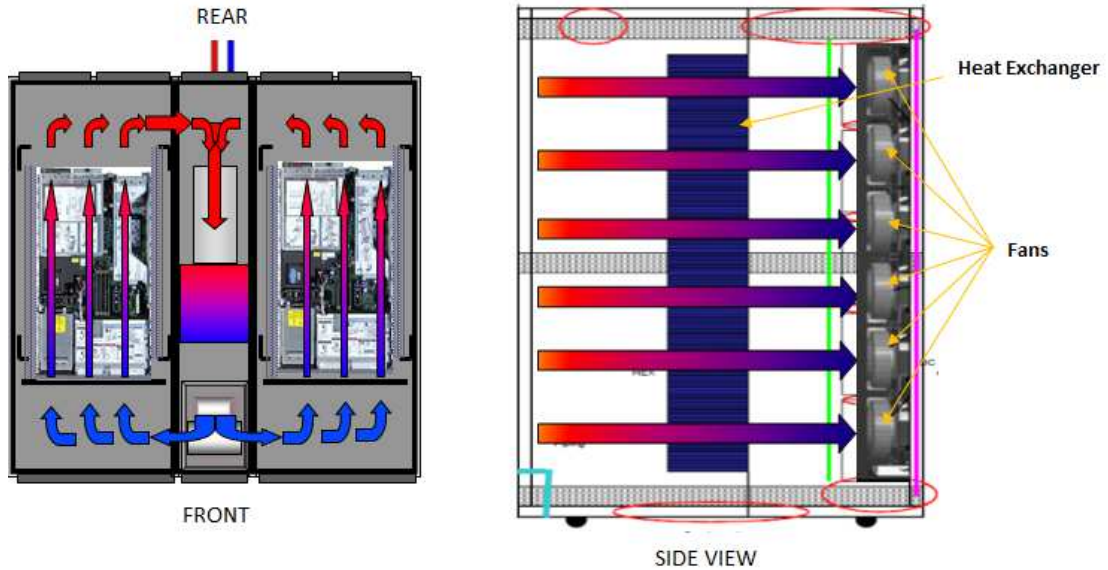
**Figure 5. Lay-outs of data centers DC1 (up) and DC2 (down).**

Again pPUE was the indicator to establish the difference between data centers. To be able to calculate partial PUE for both rooms, it was carried out flow rate measurements. Cooling water to CRAHs and WC racks came from chillers C6, C7 and C8. Old CRAHs and WC racks used cooling water from chiller C6. New CRAHs inside the datacenters used cooling water from chillers C7 and C8. Power consumption of chillers C6, C7 and C8 was divided according to flow rates of chilled water. Values based on flow rates were also compared with values based on produced energy in which temperature difference was taken into account with Equation (2). Besides cooling power and energy consumption of ITE, lighting and power loss of UPS were taken into account. Air ventilation and security and sprinkler systems were ignored because the rooms were similar.

### 8.3.1 Water cooled racks

Because capacity of air cooling is limited, the company has invested to modular cooling systems (MCS) of HP to be able to use high density racks and increase IT-load per area. In MCS, cooling energy is brought inside the rack with water cooled heat exchangers which provide cooling capacity as high as 50 kW / rack (or 25kW/rack in dual rack systems). Hot air from servers is cooled inside the racks which prevent mixing of the hot and cold air flows in the room. Maximum 10 % heat loss to ambient atmosphere from the racks is possible. Air inlet temperatures to the equipment in different heights are set constant. Water is isolated from ITE and water flows in a separated cooling unit. (HP modular cooling system 200/100 , Site preparation Guide 2014)

In MCS, there is one set parameter, the server air intake temperature, which is kept constant by adjusting cooling water flow rate and speed of the fans. This allows cooling according to demand. The flow rate of cooling water is adjusted with control valve and fans are speed-controlled. Inside the rack there is a heat exchanger where cooling water is flowing. Fans recycle air inside the rack from back to front horizontally. Air flow inside the rack is presented in the Figure 6. Ambient noise level should be 50% lower than with the conventional air cooling (Hergl 2014). To get maximum performance out of the cooling unit, the cooling water temperature should be 7 to 18 °C (HP modular cooling system 200/100 , Site preparation Guide 2014). The increase of cooling water temperature saves energy through free cooling.



*Figure 6. Up and side views of the air flow of water cooled dual rack (Hergl 2014).*

### 8.3.2 The measurements

Measurements were carried out once on 17<sup>th</sup> of December in 2014 and all used values were measured between 12.30 am and 13.30 am. Flow rates were measured with TA Scope flow meter which was adapted to a right valve type and pipe diameter. Measurements were carried out by the contractor.

Flow rates of cooling water to each CRAHs were measured as well as total flow rates of chillers C6, C7 and C8. Temperature was not measured due to the lack of suitable thermometer. Inlet and outlet temperatures of cooling water cycles were read from the control system of the building maintenance. Results of the measurements are presented in Appendix A.

Measured power consumption was only obtained for chiller C8 and its accessories. Values were recorded in every 15 minutes and average values of active power between 12.45 and 13.30 am were used. As chiller C7 was a similar system, the power consumption was approximated to be same as for C8 when the values were rated based on flow rates. Power consumption of chiller C6 was measured by analog meter. Value stayed relatively constant being 80 kW in winter, when free-cooling is not used. The power consumption of CRAHs consisted of rotating fans (1 kW) and moisturizing. Weather temperature at the measuring day was about +2 °C and air humidity was near 100 %. Either air humidification or free cooling were not used in these conditions.

Water cooled racks had a monitor where values of the cooling water inlet and outlet temperatures and flow rate, ambient temperature, cooling capacity, air inlet and outlet temperatures and speed of six fans were collected manually. The power consumption of the

dual rack consisted mainly of the energy needed to run fans and circulation pump. In a normal operation, other equipment (display, motor ball valve and controller) took only about 18 W. Power consumption of the fans were calculated on the basis of the affinity laws for the fans and relation between fan's speed of rotation ( $n$ ) and cooling capacity ( $Q$ ).

IT-load of datacenters was read manually from UPSs and distribution boards, which get electricity from main UPS of the building. Each room had two UPSs which show instantaneous values of inlet and outlet power. Energy loss in UPS could be calculated with these values. Power consumption of the lights in the data center was approximated. In both rooms, there are 25 fluorescent lamps consuming 125W each. In DC1, seven lights were broken and in DC2 two. It was assumed that lights were on during office hours, eight hours per week days.

### 8.3.3 Results

Power consumption of each CRAH was calculated using the results of flow rate measurements, temperature differences and energy consumption of chillers. To get electrical power consumption of each CRAH, electrical power consumption of chiller was divided for each CRAH based on flow rates ( $\dot{V}$ ) and heat transfer rates ( $\dot{Q}$ ) of CRAHs. Heat transfer rate ( $\dot{Q}$ ) for each CRAH was calculated with Equation (2), where density and heat capacity of water were taken at temperature  $T_{ave} = 10\text{ }^{\circ}\text{C}$  being  $\rho = 999.7\text{ kg/m}^3$  and  $c_p = 4.19\text{ kJ/kgK}$ . Thus two values for the electrical power consumption of the CRAHs were calculated called  $P_V$  and  $P_Q$ . The results of the calculations are collected in Appendix A. When comparing values of CRAH power consumption based on flow rates  $P_V$  and heat transfer rates  $P_Q$ , values differ at cooling cycle C6. The reason is that the outlet temperature of WC-racks is higher than from CRAHs. For this reason, it was used values based on energy content. The energy consumption of cooling cycles includes also pumping, but in the calculation it was not taken into account that pumping should have been divided based on the flow rate and pressure loss rather than energy content.

For the cooling process the coefficient of performance ( $COP$ ) can be calculated with Equation (10), where  $\dot{Q}$  is heat transfer rate in a chiller and  $P$  is electrical power used in chiller

$$COP = \frac{\dot{Q}}{P} \quad (10)$$

In this study,  $COP$  included also pumping energy, which is not normally included.  $COP$  for the chiller C6 was  $COP(C6) = 8.2$  and for the C7&C8  $COP(C7,C8) = 4.9$ . The difference of cooling factors was large. Results were also compared to design values of chillers. Design value for heat load of chiller C6 was 350 kW, but it was measured to be 650 kW. Chillers C7 and C8 were designed for 300 kW heat load and measured value was 430

kW. Error in the measurements could have been one likely reason for the difference of COPs between chillers C6 and C7/C8. The reason of the error could have been the lack of calibration of the flowmeter, wrong settings in meter or inappropriate method for flow measuring. Unfortunately, re-measurements were not possible to carry out. To clarify these values, flow rates and temperatures should be measured again.

The results of the water cooled racks are presented in the Appendix A. Monitored cooling capacity and fan speeds of the WC racks are compared to the values of Table 13 in Appendix A., and it was assumed that the maximum speed of fan is about 3860 rpm. It was also known that for one dual WC rack with six fans maximum current power is 13 A. Maximum load of one fan can be about 500 W corresponding the fan speed of 3860 rpm. As maximum values were known, power consumption of the fan at certain speed could have been calculated with the affinity law (Equation (11)). Manufacture's estimation of the dual rack power consumption was 1 to 2 kW. As cooling capacities of WC racks in this case were lower than the maximum cooling capacity 50 kW, energy consumption of the dual rack varied from 0.4 kW (cooling capacity being 14 kW) to 1.2 kW (cooling capacity being 21 kW). As cooling capacity would be near the maximum value of 50 kW, energy consumption of the dual rack would be about 2 kW.

$$\frac{P_1}{P_2} = \frac{V_1^3}{V_2^3} = \frac{n_1^3}{n_2^3} \quad (11)$$

Results of the IT-load are presented in Appendix A. For the datacenter's UPS 1-4 instantaneous inlet and outlet values of power were read manually from the monitor and losses of the UPSs were calculated with those values. Loss of the main UPS of the building was assumed to be 10 %.

### 8.3.4 pPUE

General equation for PUE in a datacenter was presented in Chapter 4.2. When PUE is calculated for one room, it is better to use the term partial power usage effectiveness pPUE. Value of pPUE was calculated separately for DC1 and DC2 using values described and presented above. Results are collected in Table 6. pPUE-value for DC1 was 1.46 at that certain day, and it was 7.5 % higher than value of DC2, 1.36. The difference of pPUE-values was not remarkable large, but significant difference could be seen between values of IT-load / area. As floor areas of both rooms were 140 m<sup>2</sup>, IT-load / area for DC1 was 0.93 kW/m<sup>2</sup> being 45.7 % smaller than in DC2, 1.71 kW/m<sup>2</sup>.

**Table 6. Results of pPUE calculation for datacenters DC1 and DC2 including also IT-load / area –values for both rooms.**

<b>Variables</b>	<b>DC1</b>	<b>DC2</b>
IT-load (kW)	130,4	240,0
Cooling (kW)	40,61	53,3
UPS loss (kW)	18,36	23,43
Lights (kW)	0,54	0,68
WC racks' operation (kW)		7,87
<b>pPUE</b>	<b>1,46</b>	<b>1,36</b>
<b>IT-load / area</b>	<b>0,93</b>	<b>1,71</b>

Also air temperatures in data centers DC1 and DC2 were measured in several points. Temperature level in DC1 is remarkable higher than in DC2. In DC2, temperature of hot aisle between WC racks was 26 °C, but elsewhere in the room temperatures were between 20 and 22 °C, also in hot aisles. This suggests that room is over cooled and cooling capacity could be decreased. In DC1, temperature at the screen separated cold aisle was 20 °C, but elsewhere in the room temperatures were between 27 and 30 °C. This temperature level is still allowed for the hot aisles but for the IT inlet air it is too high and may affect the reliability of ITE.

According to these measurements, the conclusion is that using water cooled racks for cooling was beneficial if needed large IT-load / area –factor is needed. For the PUE-value, use of WC racks did not have as big influence as it was supposed to be. Difference may be bigger, if traditional air cooling capacity of DC2 is reduced, and if it is taken advantage of possibility to use warmer cooling water.

### 8.3.5 Risks

Energy intensity of the data center may create new unsolved problems. Water cooled rack has a mechanism that automatically opens the door of the rack, if cooling water cycle is hindered and temperature of the rack is rising. When doors are open, heat load is rejected to the data center. Since examined data centers are relatively small, opening the doors causes rapid increasing of the ambient temperature of the room causing unpredicted fall down of the ITE in water cooled racks. In emergency situation, released heat is to be removed away to prevent unpredicted fall down of the ITE. In these data centers, exhaust air hoovers were installed above the hot aisle which direct hot air to the inlet of the old



CRAHs located in a separate room. Flow and temperature meters to cooling water inlet and outlet pipes were installed to control the system. If cooling water flow rate decreases or temperature rises, air hoover is turned on.

When cooling is brought near the servers, water leakage may cause more damages to ITE than when conventional air cooling is used. Cooling is nevertheless apart from ITE and not plug into the devices, so harm is not immediate. Interruption of cooling water or electricity cause bigger risks when heat load of the small space is high. That is why cooling backup system is more important in these kinds of areas than

## **8.4 Problems at air flow management**

General problems of airflow distribution in data centers of examined buildings are discussed in this chapter. Main problems are poor space planning together with old air handling devices. Hot and cold air are mixed leading inefficient cooling. As discussed in Chapter 8.1, cooling of data center was carried out with CRAHs, fan coil units and perforated cold air pipes. As there was no raised-floor, supply and return air from racks in an effective way has been problematic.

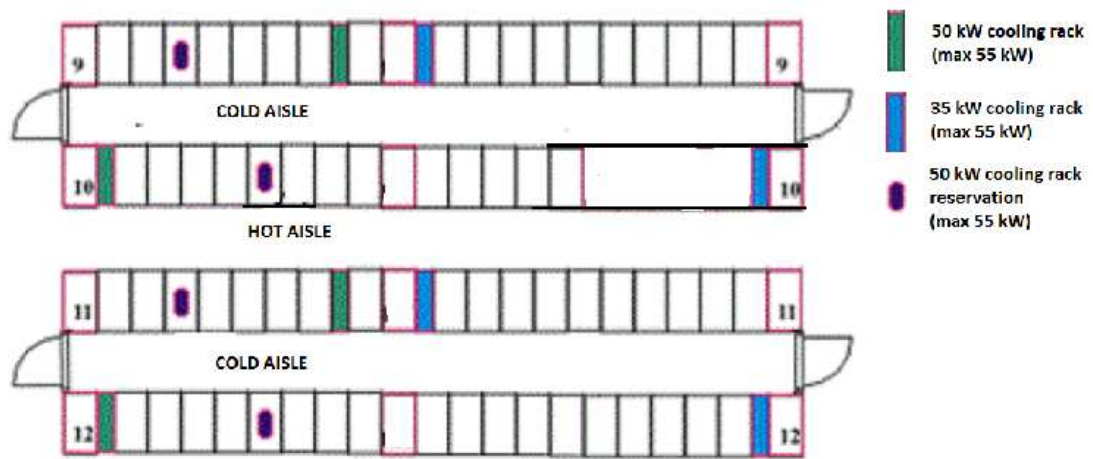
In examined buildings there are three large data centers, DC3, DC4 and DC5, and several smaller ones of which DC6 and DC7 were reviewed in airflow point of view. For the data centers DC3 and DC4 renewal of a cooling system has been planned, and it is presented and reviewed also.

One difficulty is a dynamic nature of IT business which easily leads to the unsystematic management of the ITE in the data centers. One reason for that is that the changes of ITE configuration come often sudden and unpredictable, so overall planning and management is difficult. When this is added to the fact that there is normally only two maintenance breaks during the year and all the rearrangements should be done during these weekends in addition to other maintenance work, the situation is difficult.

### **8.4.1 Data centers DC3 and DC4**

Data centers DC3 and DC4 are equipped with different IT equipment, mixed with storage areas and service areas. Cooling is carried out with CRAHs and perforated cold air pipes. Areas are large and cooling is not efficiently optimized. Part of the areas are organized to form cold and hot aisles. Nevertheless, this arrangement is not complete and some of the racks within the rows have opposite flow directions from the hot aisle to the cold aisle. That combined with inefficiently directed cooling air leads to the mixing of cold and hot air and generates hot spots. Arrangements are planned to enhance cooling performance, and give free space for other use. The goal is to increase power/area –ratio. Already now, there are empty rack places in the data centers but being scattered these do not give any savings for the rental costs.

Cooling is planned to arrange with closed cold aisles and in-line water coolers. The hot air is drawn in from the hot aisle at the rear of the rack and expelled at the front into the cold aisle after cooling. Renewed cooling arrangement is to be carried out in two steps. At first, the most efficient and renewed equipment are to be removed to the first renovated part, which consists of 8 rows of 8 racks. As space is free after the first phase, larger area with in-line water coolers and closed cold aisles for 12 rows with 20 racks per each row is renovated. Four rows of this configuration are presented in Figure 7. One option is Rittal LCP Inline CW system. Cooling water temperature used in the cooling unit can be as high as 15 °C, which enables more efficient cooling using free-cooling and district cooling without extra cooling.



**Figure 7. In-row cooling configuration.**

At the first phase, there is place for seven to eight racks and needed cooling capacity per row is approximated to be 50 kW. It is achieved with one 55 kW cooling unit (with six fan units). At the second phase, rows will be longer; 20 racks per row. In one row, there is place for two cooling units with cooling capacities 35 kW and 50 kW and reservation for one 50 kW cooling unit. After renewal, total cooling capacity would be 2020 kW, as old cooling capacity for two large data centers was 1610 kW in total. Though cooling capacity grows, the needed area is half of the original one.

Cooling capacities per rack are about 5kW and it should be considered, if it is enough and take into account the possibility of increasing capacity demand in future. Another considered aspect is that for a longer row, resistance of cooled air flow increases and efficient heat transfer may become difficult at the end of the row causing uneven temperature profile. Energy consumption of an in-line water cooler consists of provided cooling water and energy needed for cooling units. Main consumers are fans, and their energy demand depends on the rotation speed which is dependent on an air flow rate and pressure loss.

When comparing HP's water cooled racks in DC2 and Rittal's in-line water cooler, four main differences come up. In HP's solution cooling power comes closer to the heat source than in Rittal's version, which decreases power demand for air transport because fans'

power consumption is smaller. HP's version gives a constant inlet temperature before the servers. At in-line water cooler, temperature control in server's inlet is more difficult. One significant difference is the purchase price, which is double for the HP's solution, but also the solution is different. With Rittal's in line water cooler it is possible to use existing racks within the row.

### **8.4.2 Data center DC5**

Data center DC5 is a large space equipped with base stations, base station controllers and PCs for testing. Cooling of the space is executed with fan coils mounted on the ceiling and the cold air pipes from the building cooling system. ITE of the DC5 have been packed in to a smaller space, which have been led to uneven air temperature in the data center and hot spots. Temperature is measured only at some points in the large room and a failure in cooling will be detected after time delay which may cause heat up of the some systems. IT load is now maximum for receivable cooling capacity with this equipment and cooling arrangement. If IT-load needs to increase, cooling should be rearranged.

If there is some high-density racks which cause hot spots in a data center, these should be distributed among low power racks. Removing the racks next to the high power racks decreased the inlet temperature of a high powered rack and all the neighboring racks (Kumar & Joshi 2012).

### **8.4.3 Data centers DC6 and DC7**

Data centers DC6 and DC7 are small rooms. Data center DC6 has been almost empty of ITE, but temperature has been kept unnecessarily low. Some of the air handlers could be shut down or speed of the fans reduce, if possible. Near future plan is that more ITE will be located in DC6.

Air handling and cooling in DC6 was carried out with old CRAHs at the walls around the room. The CRAHs blow cold air up from the top and suck hot air from the front panel. On the side wall, cold airflow from the CRAH was obstructed with air pipes and cables so that cooling air did not reach front of the ITE. It should considered to abandon these side wall CRAHs, because of their inefficient function.

When new ITE is placed to the space, proper hot and cold aisles should be formed with no gaps between the racks and enough space between the rows. To get more efficient air handling, CRAHs should be placed perpendicular to the rack rows. Hot and cold aisles could be isolated with light wall elements and it should be considered if air ducts could be used to direct air flows in an appropriate way.

ITE in DC7 were arranged in three rows forming two cold and two hot aisles. Cold air inlets were in the ceiling. One air inlet row is located above the cold aisle but the other

one is above the hot aisle, which leads the mixing of cold and hot air. The main problem of the space is that it is too full of ITE. The space between the racks is too narrow which cause a large pressure difference causing strong upward flow in hot aisles which may circulate hot air back to front of the servers.

To guarantee sufficient cooling capacity and enhance efficiency of air flows, one row of racks should be removed. It is recommended that cold aisles should be a minimum of 4.2 m apart (center-to-center) (Kumar & Joshi 2012). To prevent mixing of hot and cold air, hot and cold aisles should be isolated with light wall elements and air flows should be directed in an appropriate way, cold air to cold aisles and hot air to inlet of CRAH.

## **8.5 District cooling**

District cooling network distributes chilled water for cooling purposes of the end users. In Finland, district cooling capacity has increased recent 10 years from 50 000 MWh to 180 000 MWh, and it is available in 8 cities. District cooling can be produced using free cooling, compressors, absorption or heat pumps. (Kaukojäähdytys) District cooling piping is to be connected to the examined building and it will take care of cooling of the building. Influences of district cooling were examined.

### **8.5.1 District cooling in examined building**

Cooling water is pumped from the lake and delivery temperature for the customers is 8 °C. Return temperature of cooling water is expected to be 16 °C. In summer and autumn, water need to be cooled to meet this target temperature. 80 % of cooling energy is obtained from the lake and that amount can be seen as a free cooling. At the first years of operations, additional cooling is done with eight portable cooling containers which are located around the city. Cooling containers are replaced by 40 MW cooling plant, which is being built and is ready at spring 2016. (Pesonen 2014)

As to an ecologic point of view, district cooling will reduce carbon footprint of building cooling. Instead of cooling with chillers run by electricity, free cooling can be utilized year around in large extend. If old chillers can be shut down, district cooling will give many positive impacts. Space is set free from the chillers and condensers. Noise level and shaking are decreased. System needs less maintenance and it is reliable. (Pesonen 2014) Reliability of the district cooling system is more than 99 % (Heikkilä, Timo 18.11.2014). When district cooling is in use, electricity power capacity can be used for other purposes, for example, increasing IT-load without installing new transformers. When old chillers are kept as a backup cooling facility, many of these benefits are lost. It should be defined, what reliability level is wanted to be fulfilled.

Heat load of a data center is remarkable, but as temperature levels are low, waste heat recovery is difficult (Ebrahimi et al. 2014). For example, Helsinki use heat pumps to raise temperature, which to utilize waste heat for the domestic heating (Mansikka 2014).

Cooling energy from the district cooling network is directed to the building's own cooling water cycles with 5 MW heat exchanger. At future, also another 5 MW heat exchanger will be installed. To fit old CRAHs and air ventilation system, cooling water needs additional cooling, and for that purpose existing chillers are used.

### 8.5.2 Effects of district cooling on PUE

Approximate calculation was carried out to clarify the effects of district cooling on PUE. Based on an example calculation in Chapter 8.2.2, and coefficient of performance (COP) 3 in summer and 10 in winter, the cooling demand in data centers was 2500 kW in summer and 2100 kW in winter. Accurate values of cooling factors of chillers in a building were not known and used values were assumptions.

Inlet temperature of district cooling water is 8 °C and temperature of the building's cooling water is about 10 °C. Since some devices require water temperature to be 7 °C, water need additional cooling from 10 °C to 7 °C, which is done with existing chillers. Temperature of returning water from the building is about 12 °C. This leads to the situation that chillers produce still 3 / 5 of cooling demand and district cooling only 2 / 5.

In district cooling system, 20 % of cooling energy is produced with portable cooling containers. Annual COP value for compressor cooling plant is approximately 2.5 (Suomen rakentamismääräyskokoelma D5 2012). Other constants and PUE-values to compare with are taken from that same example calculation. Results are presented in Table 7. Same calculation was carried out in the situation when all the devices can use 10 °C cooling water and district cooling can be used without additional cooling.

*Table 7. Effects of district cooling on PUE.*

District cooling and additional cooling with chillers		
	Summer	Winter
Cooling (kW)	580	193
IT-load (kW)	1420	1834
Other (kW)	170	167
PUE	1,528	1,196
Difference to current PUE	-11,3 %	-0,7 %
District cooling without additional cooling		
	Summer	Winter
Cooling (kW)	200	168
PUE	1,260	1,183
Difference to current PUE	-26,8 %	-1,9 %

In summer, district cooling with additional cooling would decrease the PUE value approximately 11 % compared to current situation and 27 % without additional cooling. In winter, when all the chillers are shut down and free cooling is used (outside temperature  $< -4$  °C), difference is not so remarkable. Reason is that total COP of district cooling would be about 12.5 whereas COP of building's free cooling is approximately 10. If temperature of the whole cooling water cycle can be raised, the period to utilize free cooling would be longer and total benefit of district cooling is smaller. As inlet temperature of cooling water can be higher in some devices, for example in water cooled racks, cooling water should be directed directly to devices without circulating and cooling it in chillers. This would decrease PUE value more.

Economic aspect of district cooling is also interesting. Costs of district cooling compared to the chiller cooling ran by electricity are presented in Table 8. Price of the district cooling consist of a fixed basic fee determined by the maximum water flow rate and energy fee (Heikkilä, Timo 18.11.2014). The basic fee was extrapolated from the general tariff of Tampereen Sähkölaitos. The price of the electricity was assumed to be 100 € / MWh including transmission costs and value added taxes (24 %). In this calculation, only operating costs are calculated. There is no fixed costs and investment costs included. When no additional cooling is needed, savings compared to current situation are remarkable. In the warmest summer months, difference of costs is remarkable already with additional cooling.

**Table 8. Monthly costs of cooling energy with chiller and district cooling.**

Energy prices including 24 % VAT		
	Basic fee (€/kk) (flow rate 440 m <sup>3</sup> /h)	4170
	Energy fee (€/MWh)	33
	Price of electricity and transmission (€/MWh)	100
Monthly costs of cooling (€/kk)	Summer	Winter
Current	61700	15000
District cooling + additional cooling	42100	14900
Only district cooling	9000	8200

## 8.6 Conclusions of the case study

In the case study, data centers located in a cellar of the office building in Finland were examined. Current way of calculate PUE was reviewed and improvements were suggested to get more correct values for PUE. Nighttime values of energy consumption could be used for PUE calculation to distinguish data center consumption from other uses. Power consumption of chillers and UPSs is important to measure. UPS losses should be taken into account in calculations.

For example, PUE values in winter during free cooling period and in summer were calculated using original equations and new ones. At free cooling period, the total PUE of building was about 1.2 and in warm summer day, PUE was 1.8 using new equations. During the year, PUE value lies between these values. New equations gave slightly higher PUE values. When constants are replaced by measured values, changes in heat and IT loads are taken into account more precisely.

Chiller cooling is replaced by free cooling in winter. With free cooling significant energy saving are achieved as can be seen from PUE values presented at previous chapter. Use of free cooling in these buildings could be more efficient. Manual operation of free cooling hinders effective use, because free cooling was not turned on only for a one day and during weekends. Possibility to use both free cooling and chiller together should be examined. Temperature limit for free-cooling is often kept too low. It should be considered, if this limit is possible to raise.

Two data centers were compared to get out information about the efficiency of water cooled racks compared to traditional air cooling. To be able to distribute energy consumption for these rooms, flow rates of cooling water going to each CRAHs were measured as well as total flow rates of chillers. Measurements were carried out once on 17<sup>th</sup> December, 2014 and all used values were instantaneous. There was a doubt that especially measured flow rates of chillers are too high. To clarify these values, i.e. flow rates and if possible temperatures should be measured again.

PUE-value of air cooled data center was 1.46, and it was 7.5 % higher than value of other data center, 1.36, which was partly roomed with water cooled racks. PUE of building B at the same day was 1.53. The difference in PUE-values was not remarkable large, but significant difference could be seen between the values of IT-load / area. In traditional air cooled data center, IT-load / area was 0.93 kW/m<sup>2</sup> being 45.7 % smaller than in a partly close liquid cooled data center, 1.71 kW/m<sup>2</sup>.

According to these measurements, conclusion was that using close liquid cooled racks for cooling is beneficial if IT-load / area –factor is large. For the PUE-value, use of WC racks did not influence significantly. Influence may have been bigger, if normal air cooling had been reduced or even shut down partly in DC2. It should be noticed that it was not taken into account that water cooled racks can use warmer cooling water which enables to use free-cooling for a longer time and decreases the need of an additional cooling with district cooling. These facts would reduce energy used for cooling.

Studied building is connected to the district cooling network. Approximate calculations of effects of the district cooling on the PUE-value and operating costs of cooling were made. Without renewing cooling devices, additional cooling is needed to meet temperature requirement of cooling units and this additional cooling is done with old chillers.

During free-cooling period, difference was not remarkable but in summer PUE may decrease to 1.5 with additional cooling and to 1.3 if cooling can be done completely with district cooling. Operating costs in summer at current situation are approximately 62 000 €/month and those will reduce to 42 000 €/month after first phase and to 9 000 €/month if cooling can be done completely with district cooling. District cooling would bring savings and reduce PUE-value especially in summer.

In this study, rearrangements plans with in-line coolers for DC3 and DC4 were presented. Airflow problems in DC5, DC6 and DC7 were discussed. Generally, the most important tasks to improve energy efficiency are to avoid unnecessary cooling of data centers and to prevent mixing of hot and cold air.



## 9. CONCLUSIONS

Data centers form a base of the telecommunication industry. Energy consumption of data centers is already globally significant as data centers consume 1.1-1.5 % of world's electricity use in 2010 (Koomey 2011), and about 40 % of that is used for cooling (Dai et al. 2014). Enhancement of data center cooling has good potential to reduce energy consumption and greenhouse gases of telecommunication industry.

Facilities of data center must operate such that environmental conditions of the data center can be ensured. Requirements for the air temperature, its stability, humidity and dust come from manufactures and standards as well as ASHRAE Thermal Guidelines, which try to ensure reliable, safe and efficient operation of ICT systems. With thermal and airflow management conditions in data centers can be retained suitable even thermal loads are increased. Dynamic nature of IT business combined to the short lifecycle of servers compared to facilities cause mismatches and complicate planning. Airflow managing must balance both thermal environment and energy savings.

Efficiency metric PUE has become as a standard in data center industry over time and is the most commonly used metric for reporting energy efficiency of data centers (Brady et al. 2013). For this reason, PUE was used as a reference value in the case study also. It was examined how changes in cooling system would effect PUE-value compared to the original one, which varied between 1.2 and 1.8. It should be kept in mind that PUE tells more about weather and climate than real effectiveness of data center when compared to data centers in other locations.

Combining IT and facility monitoring is the key to solve problems in data center such as device placement, equipment maintenance, energy efficiency and utilization, (Bhattacharya 2012, p. 200) but comprehensive monitoring is demanding. One goal of the case study was to improve and evaluate PUE calculations in buildings. Cooling system of examined building consisted of multiple cycles and devices. With current monitoring, it was impossible to precisely separate energy used for data center cooling and energy used for cooling and ventilation the rest of the office building. A more detailed configuration and continuous real-time monitoring would require more measurements and monitoring. It should be considered, if benefits of more accurate PUE-values are greater than costs followed from more detailed monitoring. With small changes in PUE-calculations, values can be corrected. Nighttime power consumption should be used in calculations and power consumption of two chillers and UPS, which were originally added as a constant, should be measured. Also power losses of UPS should be taken into account in total facility energy, not in IT equipment energy.

Inside the data center air cooling has been predominant technology but as power and cooling demand have increased, capability of air cooling has exceeded and alternatives are needed. Close liquid cooling, direct liquid cooling and two-phase cooling could be alternatives to the traditional air cooling. In the close liquid cooling, cooling cycle is near or inside the server racks, but not in contact with heat-generating components. In the direct liquid and phase change cooling, heat-generating components are in thermal contact with circulating coolant in cold plates. In the case study, efficiency of close liquid cooling and traditional air cooling were compared with the single measurement. According to the measurement, use of closed liquid cooling racks for cooling is beneficial if there is need for large IT-load / area -factor. For the PUE-value, use of closed liquid cooled racks did not influence significantly.

Traditional vapor compression cooling systems are energy intensive and consume energy all year round, even at night and in winter when temperature is low. Free cooling utilize natural cold source, such as outdoor air or water, to cool data center in economical, ecological and sustainable way. Direct and indirect economizers as well as heat pipes can be used in free cooling. Values of PUE in winter during free cooling period and in summer showed good potential of free cooling to save energy. At free cooling period, total PUE of building was about 1.2 and in warm summer day equal to 1.8 with new equations. Use of free cooling in these buildings could be more efficient. Temperature to turn on free cooling may be higher, and potential to use both free cooling and chiller together should be examined. As building is connected to the district cooling network, free cooling can be utilized also in summer. But without renewing cooling devices, additional cooling with chillers is still needed to meet temperature requirement of cooling units. In summer, district cooling could decrease PUE-value to 1.5 with additional cooling and to 1.3 if cooling could be done completely with district cooling. In winter, the effect would be lower as free cooling has also been in use at the moment.

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## APPENDIX A: RESULTS OF MEASUREMENTS AND CALCULATIONS TO DETERMINE PARTIAL-PUE IN DC1 AND DC2

*Table 9. Results of the measurements on 17<sup>th</sup> December, 2014.*

Chiller / CRAH	D	V	dp	T <sub>in</sub>	T <sub>out</sub>	P
	mm	l/s	kPa	°C	°C	kW
<b>C6</b>	150	39,34	2,20	11,8	7,8	80
<b>C7</b>	125	19,11	1,75	12,3	7,2	
<b>C8</b>	125	19,99	1,91	12,2	7,1	61,53 Chiller
						25,71 Accessories
<b>DC1</b>	<b>CRAH1</b>	80	5,47	0,71		
	<b>CRAH2</b>	65	2,21	0,52		
	<b>CRAH3</b>	65	2,93	0,914		
	<b>CRAH4</b>	65	1,88	0,375		
<b>DC2</b>	<b>CRAH5</b>	65	2,21	0,52		
	<b>CRAH6</b>	80	5,81	0,638		
	<b>CRAH7</b>	65	1,73	0,316		
	<b>CRAH8</b>	65	1,89	0,382		

**Table 10. Results of calculations based on measured flow rates ( $V$ ), temperature difference ( $\Delta T$ ) and electrical power ( $P$ ). Measured values and recorded values are bolded.**

		$V$	$x_v$	$P_v$	$T_{in}$	$T_{out}$	$dT$	$\dot{Q}$	$x_Q$	$P_Q$	$\varepsilon_p$
		l/s	%	kW	°C	°C	°C	kW	%	kW	
<b>C6</b>	Total	<b>39,34</b>	100 %	<b>80</b>	<b>11,8</b>	<b>7,8</b>	<b>4,00</b>	659,1	100 %	<b>80</b>	8,24
DC1	CRAH1	<b>5,47</b>	14 %	11			4,00	91,6	14 %	11	
	CRAH2	<b>2,21</b>	6 %	4			4,00	37,0	6 %	4	
DC2	CRAH5	<b>2,21</b>	6 %	4			4,00	37,0	6 %	4	
	CRAH6	<b>5,81</b>	15 %	12			4,00	97,3	15 %	12	
	WC racks	4,63	12 %	9	7,9	15,2	7,3	141,7	21 %	17	
Rest		27,03	69 %	55				254,4	39 %	31	
<b>C7</b>	Total	<b>19,11</b>	49 %	<b>83,39</b>	<b>12,3</b>	<b>7,2</b>	5,1	408,2	49 %	<b>83,39</b>	
<b>C8</b>	Total	<b>19,99</b>	51 %	<b>87,24</b>	<b>12,2</b>	<b>7,1</b>	5,1	427,0	51 %	<b>87,24</b>	4,90
<b>Total</b>		39,1	100 %	170,63				835,3	100 %	170,63	
DC1	CRAH3	<b>2,93</b>	7 %	12,79			5,1	62,6	7 %	12,79	
	CRAH4	<b>1,88</b>	5 %	8,20			5,1	40,2	5 %	8,20	
DC2	CRAH7	<b>1,73</b>	4 %	7,55			5,1	37,0	4 %	7,55	
	CRAH8	<b>1,89</b>	5 %	8,25			5,1	40,4	5 %	8,25	
Rest		34,44	88 %		12,2	7,1	5,1	735,7	88 %	150,29	



**Table 11. Monitored values of water cooled racks and calculated power consumption of fans.**

Number of rack	$T_{\text{water,IN}}$ °C	$T_{\text{water,OUT}}$ °C	$V$ l/min	$x$ %	$Q$ kW	$T_{\text{air,IN, set}}$ °C	$T_{\text{air,IN}}$ °C	$T_{\text{air,OUT}}$ °C	Number of fan	rpm $n$	W $P$ (calculated)
1	9	15	47	55	20,9	23	29	21	1	2700	170
									2	2680	166
									3	2700	170
									4	2700	170
									5	2700	170
									6	2700	170
2	8	13	51	57	19,7	23	30	22	1	2860	202
									2	2840	198
									3	2880	207
									4	2860	202
									5	2840	198
									6	2820	194
3	8	15	51	58	25,1	23	30	22	1	2960	224
									2	2920	215
									3	2920	215
									4	2880	207
									5	2920	215
									6	2860	202
4	8	14	41	56	18,7	23	30	22	1	2900	211
									2	2940	220
									3	2940	220
									4	2900	211
									5	2940	220
									6	2920	215
5	6	13	29	37	13,5	19	30	21	1	1840	54
									2	1820	52
									3	1780	49
									4	1820	52
									5	1840	54
									6	1800	50
6	7	16	22	25	13,7	23	33	25	1	2040	73
									2	2040	73
									3	2040	73
									4	2060	76
									5	2060	76
									6	2040	73
7	8	21	18	22	14,8	25	32	26	1	2055	75
									2	2040	73
									3	2055	75
									4	2025	72
									5	2025	72
									6	1965	66
8	9	18	19	21	12,6	23	33	24	1	2040	73
									2	2080	78
									3	2040	73
									4	2000	69
									5	2030	72
									6	2040	73

**Table 12. IT-loads of DC1 and DC2, and UPS's loss.**

		$P_{IT,OUT}$	$P_{IT,IN}$	Loss	
		kW	kW	kW	%
<b>DC1</b>	UPS1	51,2	59	7,8	13,2 %
	UPS2	37,6	44	6,4	14,5 %
	Distribution boards	41,6			10,0 %
<b>DC2</b>	UPS3	87,1	98	10,9	11,1 %
	UPS4	73,5	77,3	3,8	4,9 %
	Distribution boards	87,3			10,0 %

**Table 13. Approximate fan step at certain cooling capacity (HP modular cooling system 200/100 , Site preparation Guide 2014).**

Approximate cooling capacity	Approximate fan speed
~9 kW	40–45%
~24 kW	75–85%
~32 kW	90–100%
>40 kW	100 %